Analysis of Mo Sidewall Ohmic Contacts to InGaAs Fins

by

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Abstract

As transistor size is scaled down, the performance is degraded and many problems, so called short-channel effects, arise. To address this problem, a vertical transistor structure such as vertical nanowire is suggested. In a vertical nanowire field-effect-transistor, the Ohmic contact at the top of the nanowire not only covers the top surface, but also wraps around the sidewall. Because the sidewall is considered to be different from the top surface, it is necessary to study the sidewall Ohmic contact properties such as the contact resistivity.

In this thesis, to explore sidewall contact resistivity, a theoretical model for sidewall contacts is developed. For the suggested test structure, the fin sidewall contact (FSWC) structure, the sidewall contact is modeled with a transmission line model (TLM), and by using TLM, the sidewall contact resistance is derived. Also, an extraction method of the sidewall contact resistivity from the total resistance measured in FSWC structure is developed. Next, process steps to fabricate FSWC structure are developed. FSWC structure is made for Mo/n'-InGaAs contacts. The key step is that the fin etch mask on top of InGaAs is not removed and the metal (Mo) is sputtered so that InGaAs is contacted by the Mo only through the sidewall. Therefore, only a sidewall contact is made without a top contact. Also, to investigate the way to improve the sidewall contact resistivity, the effect of digital etch and annealing on the sidewall contact resistivity is explored.

With the measured total resistance in FSWC structure and the extraction method for sidewall contact resistivity, sidewall contact resistivity for each split of digital etch and annealing are extracted. As a summary of the effect of digital etch and annealing, two cycles of digital etch or sequential annealing up to 400 °C improves the sidewall contact resistivity with little sacrifice in semiconductor resistivity. The best result of sidewall contact resistivity is 3.7±0.01 Ω · μm² at 400 °C annealing, which is about 1.9 times improvement over the non-annealed value, 6.9±0.05 Ω · μm² but still about 5.4 times larger than the reported top contact resistivity of 0.69±0.3 Ω · μm².

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CHAPTER 1. Introduction

1.1 Emergence of vertical channel transistors

In modern transistors, a major trend has been scaling down the size of the semiconductor device to get advantages such as higher device density and lower supply voltage. But as the device size becomes smaller, lots of problems, in particular short-channel effects, have arisen. For example, because as the channel length becomes shorter, the effect of electric field from source and drain to channel becomes larger. So the control of the gate over the channel decreases and problems such as drain induced barrier lowering (DIBL) and threshold voltage shifting occur. Also, because scaling reduces the distance between metal lines, the overall size of semiconductor device becomes smaller. Consequently, the size of source and drain becomes smaller, so the contact resistance of source and drain becomes larger.

To address these problems, the device foot-print and the direction of transport need to be decoupled, so a vertical channel device was suggested. Because the channel of a vertical channel device is normal to the wafer surface, channel length and device footprint scaling can be separated. So short-channel effects no longer worsen as the foot-print decreases. Another significant advantage of vertical devices is that there is more room for source and drain contacts since they no longer add to the device foot-print. This should result in improved contact resistance over that of the planar device. For vertical channel devices, vertical fin or nanowire field-effect-transistor (FET) are possible schemes and the latter has been heavily investigated. With the improvement of subthreshold slope by taking gate-all-around (GAA) structure, vertical nanowire FET is expected to outperform compared with planar fin or nanowire scheme beyond 7 nm node [1]. Recently, there was a report comparing performance of lateral finFET, lateral GAAFET (nanowire FET) and vertical GAAFET [1]. In this study, the vertical GAAFET shows the best node-to-node scalability,
power and area reduction beyond the 7 nm node. Therefore, vertical channel devices, especially vertical nanowire FETs, are expected to be next generation device scheme due to several advantages such as mitigation of short-channel effects and enough room for source and drain contacts by decoupling channel and footprint direction as well as improvement of subthreshold swing by GAA scheme.

1.2 Sidewall contact

In the investigation of vertical nanowires, the components such as resistance and capacitance that are required for modeling the device with an equivalent circuit model need to be investigated. At first, contact resistance which is one component of device resistance should be tackled. For example, in the vertical nanowire scheme implemented in [2], there are two contacts which are formed at the top and beside the nanowire (source and drain contacts). As the contact in a planar device, the contact beside the nanowire covers the top surface of n'-InGaAs. However, at the top of the nanowire, the metal is not only contacted at the top surface, but also wraps around the sidewall. In both cases of top-down (etch) and bottom-up (growth) approaches for vertical nanowire fabrication, the contact that wraps around the sidewall of the nanowire (sidewall contact) may have different properties such as contact resistivity compared with the contact covering the top surface (top contact). Especially, in top-down approach, the properties of the sidewall contact are expected to be worse than those of the top contact as a result of sidewall damaged by plasma during nanowire etch. Therefore, it is important to investigate the properties of the sidewall contact not only to model it but also to develop processes to optimize it. As the first step, it can be good start to study the way to measure and improve the contact resistivity of the sidewall contact.

1.3 Previous studies

There are some studies about contact resistivity for vertical structures. In [3], contact resistivity of the Ni contact at the top of the nanowire is extracted for bottom-up InAs nanowires. They reported
0.6 Ω·μm² as their best result for contact resistivity with annealing at 300 °C for 1 min. In [4], two schemes with metal covering only the top surface or both top surface and sidewall of fin structure are studied for Mo/n⁺-InGaAs contact.

In both studies, contact covering both top surface and sidewall of vertical structure is explored, and they did not distinguish top and sidewall contacts. To investigate sidewall contact, it is needed to develop methods to fabricate a test structure with only sidewall contact. In addition, it is necessary to construct a theoretical model to extract contact resistivity of sidewall contact from the structure.

1.4 Thesis outline

In this thesis, Mo/n⁺-InGaAs sidewall contacts are investigated. InGaAs is considered as promising material for n-type channel devices [5]. In Chapter 2, a theoretical model for sidewall contact with fin structure is developed. Basics of metal-semiconductor contact and contact resistance is discussed and a transmission line model (TLM) for the top contact is reviewed. Then, TLM for sidewall contact with fin structure is developed and extraction methods for sidewall contact resistivity is described. In Chapter 3, fabrication steps to implement a structure with only sidewall contacts is described. The key point is that, after fin dry etch, the electron beam lithography mask that is used to define the fin is not removed and the metal contact is sputtered so that the active layer is only connected with metal contact at the sidewall. In Chapter 4, experimental results and analysis are presented. For measurements, a four-probe (Kelvin) resistance measurement scheme is used. The results of extraction of the several parameters including contact resistivity are described, and the effect of digital etch and annealing on contact resistivity to improve the contact resistivity is explored. In Chapter 5, several issues are discussed. Finally, in Chapter 6, key points of this study are summarized and several future research topics are suggested.
CHAPTER 2. Theoretical model for fin sidewall contact

2.1 Introduction

In this chapter, we build transmission line model for fin sidewall contact (SCTLM). SCTLM has two contacts on both sides of a fin and can be modified to transmission line model for top contact (TCTLM). Also, we develop extraction method for sidewall contact resistivity, which is used in Chapter 4.

2.2 Metal-semiconductor contact and contact resistance

Depending on the relative magnitude of the work functions for the semiconductor and the metal, there can be two cases of metal-semiconductor contacts: Schottky and Ohmic contact in figure 2.1 (a) and (b), respectively. As depicted in figure 2.1 (c), if the contact is a Schottky contact, when voltage is applied, electron flow is impeded by barrier. As the applied voltage increases, the barrier height decreases, and the current turns out to be exponentially dependent on the forward bias voltage ([6], p. 490). So voltage and current are not linear and it can be considered that the contact resistance is voltage dependent. But as depicted in figure 2.1 (d), if the contact is an Ohmic contact, there is no barrier and the contact resistance does not depend on the applied voltage. In reality, Schottky contact can be used as an Ohmic contact by using semiconductor with high doping at the surface, which makes very narrow Schottky barrier to allow electrons to tunnel through. Basically all contacts in a device need to function as Ohmic contact.
Even if an Ohmic contact does not have a barrier in the energy band diagram, because the surface is changed from semiconductor to metal, there is a contact resistance as follows:

$$R_c = \frac{\rho_c}{A}$$  \hspace{1cm} (2.1)

where $\rho_c$ is the contact resistivity which models properties of the contact surface and $A$ is the normal area to current flow. Equation (2.1) is applied for uniformly flowing current which is normal to cross-section with area $A$. For planar transistor, current flow direction in channel is perpendicular to that at metal and semiconductor interface, so equation (2.1) is not applicable and current is crowded to one edge of the contact closer to the channel, as shown in figure 2.2 (a). To model a transistor contact, a distributed resistor model, so called transmission line model (TLM), is needed.
2.3 TLM for top contact

TLM for top contact (TCTLM) is a distributed resistor model, as shown in figure 2.2 (b). In this model, the metal resistance is ignored and the active layer is assumed to be thin. The differential resistance of the active layer under the metal and the differential conductance across the interface of the metal and the active layer can be modeled as \( dR \) and \( dG \), respectively. If appropriate coordinate is set for TLM as depicted in figure 2.2 (b), Kirchoff voltage and current laws can be used at point \( x \) as follows [9].

\[
dV(x) = -I(x) dR = -I(x) \frac{R_{sh}^*}{W} dx
\]  

Figure 2.2 (a) Cross section of contact and channel of transistor (b) Transmission line model for contact (reproduced from [8] and modified by author).
\[ dl(x) = -V(x)dG = -V(x)\frac{W}{\rho_c} dx \quad (2.3) \]

Superscript 't' refers to top contact. If equations (2.2) and (2.3) are solved with boundary conditions, \( I(0) = I_0 + dI(0) \approx I_0 \) and \( I(L_c) = 0 \), then \( I(x) \) and \( V(x) \) can be derived. The results are as follows [9]:

\[ I(x) = I_0 \left[ \cosh \left( \frac{x}{L_T^T} \right) - \coth \left( \frac{L_c}{L_T^T} \right) \sinh \left( \frac{x}{L_T^T} \right) \right] \quad (2.4) \]

\[ V(x) = \frac{\sqrt{R_{sh}\rho_c L_T^T}}{I_0} \left[ \cosh \left( \frac{L_c}{L_T^T} \right) \cosh \left( \frac{x}{L_T^T} \right) - \sinh \left( \frac{x}{L_T^T} \right) \right] \quad (2.5) \]

where \( L_T^T = \sqrt{\rho_c R_{sh}} \) which is called the transfer length. The transfer length can be considered as an effective contact length. It means that considerable amount of current enters contact within \( x \leq L_T^T \). The sum of normalized current entering contact within \( x \leq L_T^T \) is as follows.

\[ \int_{0}^{L_T^T} \frac{dI(x)}{I_0} \bigg|_{x=0}^{L_T^T} = \int_{0}^{L_T^T} \frac{V(x)W}{I_0 \rho_c} dx = \cosh(1) - \cosh(0) - \coth \left( \frac{L_c}{L_T^T} \right) \sinh(1) \quad (2.6) \]

For \( L_c \geq L_T^T \), the graph of \( \int \frac{dI(x)}{I_0} \bigg|_{x=0}^{L_T^T} \) is as follows.

Figure 2.3 \( \int \frac{dI(x)}{I_0} \bigg|_{x=0}^{L_T^T} \) vs. \( \frac{L_c}{L_T^T} \).
If $L_c/L_T \gg 1$, cotangent hyperbolic term becomes nearly unity, then $\left| \int dI(x)/I_0 \right|_{x=0}$ converges to $|\cosh(1) - \cosh(0) - \sinh(1)| \approx 0.63$. Therefore, for $L_c \geq L_T$, over 63% of the total current enters contact within $x \leq L_T$, which justifies the name of $L_T$, ‘transfer length’.

By using equation (2.4) and (2.5), the contact resistance of the top contact between points A and B in figure 2.2 (b) can be derived as follows [9]:

$$R_c^t = \frac{V(0)}{I_0} = \frac{\sqrt{R_{sh}^c \rho_c^t}}{w} \coth\left(\frac{L_c}{L_T}\right)$$  \hspace{1cm} (2.7)

When $L_c \gg L_T$, cotangent hyperbolic term becomes nearly unity and equation (2.7) can be simplified as follows [9].

$$R_c^t \approx \frac{\sqrt{R_{sh}^c \rho_c^t}}{w}$$  \hspace{1cm} (2.8)

From equation (2.8), $R_c^t$ becomes independent on $L_c$ when $L_c \gg L_T$. With the structure in figure 2.2 (a), the total resistance ($R_{tot}$) from one metal contact to the other metal contact is as follows:

$$R_{tot} = R_{ch} + 2R_c^t = \frac{\rho_s}{T \cdot W} L_{ch} + 2R_c^t$$  \hspace{1cm} (2.9)

![Figure 2.4 $R_{tot}W$ vs. $L_{ch}$ graph (reproduced from [8] and modified by author).](image)
where \( R_{ch} = \frac{\rho_s}{T_W} L_{ch} \) is the resistance of the channel. Several structures such as that of figure 2.2 (a) can be designed with different channel length, and the normalized current, \( I_0/W \), can be measured. Then if \( R_{tot} W \) is plotted vs. \( L_{ch} \), then figure 2.4 is obtained. From the slope and y-intercept of \( R_{tot} W \) vs. \( L_{ch} \), \( R_{th}^t \) and \( 2R_{th}^f \) are extracted, respectively. If \( L_c \gg L_T \) and \( R_{th}^c \) of the channel is the same as that of the active layer under the metal, the contact resistivity, \( \rho_c^t \), can be extracted by substituting the value of the slope for \( R_{th}^t \) in equation (2.8).

Although the TLM is a useful tool to model contact resistance, the dimension of the structure needs to be carefully checked to make sure the assumptions are valid. In the TLM, the following two assumptions are made:

1) Because the active semiconductor layer under the metal is modeled with one dimensional resistance series which is parallel to the metal-active layer interface, it is assumed that there is no vertical voltage drop in the active layer under the metal.

2) Because the TLM includes the semiconductor active layer only under the metal (figure 2.2 (b)), no current over-spreading is assumed (current over-spreading indicates current flux lines which are curved farther than the contact. It is shown in figure 2.5 (a).)

To deal with the first assumption, there is the extended TLM (ETLM), which includes the vertical voltage drop in the semiconductor [10]. Vertical voltage drop is modeled by adding a partial vertical semiconductor resistance of unit area to the contact resistivity as follows:

\[
\rho_c^t + C \cdot \rho_s T
\]  

\[ (2.10) \]

Figure 2.5 (a) Prediction of real current flow in the active layer under contact (reproduced from [11] and modified by author), (b) current flow with assumptions in TLM.
where \( C \) is a constant which is less than unity and \( \rho_s T \) is the vertical semiconductor resistance per unit area. The contact resistance in ETLM with \( L_c \gg L_T^e \) is obtained by substituting \( \rho_c^e \) in equation (2.10) for \( \rho_c^e \) in equation (2.8) and the result is as follows:

\[
R_c^e \approx \frac{R_{sh}^e \rho_c^e}{w} = \frac{R_{sh}^e (\rho_c^e + C \cdot \rho_s T)}{w}
\]  

(2.11)

If a unitless parameter \( \eta = \frac{\rho_c^e}{\rho_s T} \) is defined, which indicates the ratio between the contact resistance and the vertical semiconductor resistance per unit area, then equation (2.11) becomes as follows:

\[
R_c^e \approx R_c^e \sqrt{1 + \frac{C}{\eta}}
\]  

(2.12)

A reasonable value for \( C \) is 0.19 [10]. If an error smaller than 10% is allowed for the TLM compared with the ETLM, then the following inequality needs to be satisfied.

\[
0.9 \cdot R_c^e \sqrt{1 + \frac{C}{\eta}} \leq R_c^e
\]  

(2.13)

If equation (2.13) is solved for \( \eta \), it results in as follows.

\[
\eta \geq 0.81
\]  

(2.14)

If equation (2.14) is rearranged, then

\[
T \leq \frac{1}{0.81 \rho_s} \frac{\rho_c^e}{\rho_c^e}
\]  

(2.15)

From equation (2.15), in order for the TLM to be applied, the thickness of the active layer needs to be restricted by the ratio between the contact and the semiconductor resistivity.

For the second assumption, to reduce current over-spreading, the contact needs to be sufficiently long. For appropriate criteria of long contact length, \( L_c \gg L_T^e \) can be selected, which indicates the effective contact length. Then the condition, \( L_c \gg L_T^e \), can be set to reduce current over-spreading. If \( L_c \gg L_T^e \) is rearranged, the following condition comes out.

\[
\frac{L_c}{T} \gg \sqrt{\eta}
\]  

(2.16)
From equation (2.16), like equation (2.15), the condition for small current over-spreading gives, again, a criteria for the dimension of the structure. Combining the two conditions for \( \eta \), we have:

\[
0.81 \leq \eta \ll \left( \frac{L_c}{L_T} \right)^2
\]  

(2.17)

Note that the inequality on the left side is derived under the assumption of \( L_c \gg L_T \) which is equivalent to the inequality on the right side.

There can be more assumptions for TLM which can make more conditions other than equation (2.17). Therefore, in practical point of view, it is better to use numerical method. For instance, TLM and two dimensional resistor mesh can be compared via HSpice simulation. From this result, whether TLM is available or not for the fabricated TLM structures can be figured out. However, equation (2.17) is still useful for quick check when we design TLM structures.

### 2.4 TLM for fin sidewall contact

Sidewall contact is the contact on the sidewall of a vertical structure such as a fin and nanowire. Because sidewall surface of fin and nanowire structure can be different from the as-grown top surface, sidewall contact and top contact need to be considered separately. Because, current flow direction through sidewall contact is perpendicular to that in channel, a distributed resistor network to model the sidewall contact needs to be used. To investigate sidewall contact modeled by distributed resistors, one possible structure is fin structure with sidewall contacts as shown in figure 2.6 (a). TLM for sidewall contact (SCTLM) is shown in figure 2.6 (b). As depicted in figure 2.6 (a), because voltage is applied symmetrically for the axis along the longer side of the active layer, circuit in figure 2.6 (b) is symmetric along the axis. Therefore, the circuit can be folded with the axis and it becomes the circuit shown in figure 2.6 (c). Because the upper and lower \( dG \) are connected in parallel, they are combined and become \( 2dG \). If the circuit in figure 2.6 (c) is compared with TCTLM in figure 2.2 (b), then the circuits become the same if \( W \rightarrow 2T, T \rightarrow W_f/2 \) are applied to TCTLM. \( R_{sh}^{SW} \) becomes as follows.
Figure 2.6 (a) TLM structure of fin with sidewall contacts, (b) TLM for sidewall contact, (c) folded circuit from (b) (superscript 'sw' indicates sidewall contact).

\[ R_{sw}^{sh} = \frac{\rho_s}{W_f/2} \]  

(2.18)

Here, the superscript 'sw' refers to sidewall contact. Also, from equation (2.7), the resistance between points A and B in figure 2.6 (c) is as follows.

\[ R_c^{sw} = \sqrt{\frac{\rho_c^{sw}}{2T}} \frac{L_c}{L_T^{sw}} \coth \left( \frac{L_c}{L_T^{sw}} \right) \]  

(2.19)

where \( L_T^{sw} = \sqrt{\rho_c^{sw}/R_{sw}^{sh}} \). When \( L_c \gg L_T^{sw} \), equation (2.19) becomes as follows.

\[ R_c^{sw} \approx \sqrt{\frac{\rho_c^{sw}}{2T}} \]  

(2.20)

Actually, the part in black dashed box in figure 2.6 (a) can be seen as a parallel connection of two resistors where one resistor corresponds to the upper half and the second to the lower half. Because parallel connection gives half value of the resistance of a single resistor, this is the reason of one half term on the right hand side of equation (2.19).
As we did for the TCTLM, a similar plot to figure 2.4 can be drawn. With the structure in figure 2.6 (a), the total resistance \(R_{tot}\) from one contact to the other contact along the fin length is as follows:

\[
R_{tot} = R_{ch} + 2R_{c}^{sw} = \frac{\rho_{s}}{T \cdot W_f} L_f + 2R_{c}^{sw} \tag{2.21}
\]

where \(R_{ch} = \frac{\rho_{s}}{T \cdot W_f} L_f\) is the resistance of the channel or fin. Several structures depicted in figure 2.6 (a) can be designed with different fin lengths, and the normalized current, \(I_0/T\), can be measured (note that the normalization factor is \(W\) for TCTLM, but it is changed to \(T\) in SCTLM). Then \(R_{tot} T\) can be calculated, which gives figure 2.7 for \(R_{tot} T\) vs. \(L_f\). From the slope and \(y\)-intercept of \(R_{tot} T\) vs. \(L_f\), \(\frac{1}{2} R_{sh}^{sw} + 2R_{c}^{sw} T\) can be extracted, respectively. If \(L_c \gg L_{sw}^{T}\) and \(R_{sh}^{sw}\) of the channel is the same as that of the active layer under the metal, the contact resistivity, \(\rho_{c}^{sw}\), can be extracted by substituting twice of the slope value of \(R_{tot} T\) vs. \(L_f\) to \(R_{sh}^{sw}\) in equation (2.20). One thing we need to keep in mind is that if \(W_f\) is too wide, then the TLM is not applicable. Thus, if \(W_f\) is changed as a parameter, it would be good to check (rough) available \(W_f\) range by using equation (2.17) with estimated \(\rho_{c}^{sw}\) and \(\rho_{s}\) from the literature when the structure is designed.

One interesting point is that the actual current flux can be divided into two kinds: flow into metal contact in the same side of fin \((I_{||})\) and in the opposite side of fin \((I_{\perp})\) depicted in figure 2.6 (a). They are certain portion of total current, and those portions are determined by resistance ratio.
between $R_\parallel$ and $R_\times$ which correspond to $I_\parallel$ and $I_\times$, respectively. Roughly, $R_\parallel$ and $R_\times$ are proportional to $L_f$ and $\sqrt{L_f^2 + W_f^2}$, respectively. Because $I_\times = \frac{R_\parallel}{R_\parallel + R_\times} I_0 \approx \frac{1}{1 + (W_f/L_f)^2} I_0$ where

$I_0$ is total current, as $W_f/L_f$ becomes larger, $I_\times$ becomes smaller. If $L_f$ is fixed and $W_f$ increases, then, after certain $W_f$, $I_\times$ becomes very small and effective $W_f$ may become saturated. This effect is expected to be seen easily from the saturation of slope $\left(\frac{1}{2} R_{sw}^{sw}\right)$ in $R_{tot} T$ vs. $L_f$ graph (figure 2.7). This means that, effectively, the current does not use the whole fin width if $W_f/L_f$ is large. (This is not done in this study and suggested as a future work in Section 6.2.) This two-dimensional effect can be simulated with a two-dimensional resistor mesh in HSpice.

### 2.5 Extraction method for sidewall contact resistivity

The usual method to extract contact resistivity is as follows. From the $y$-intercept and slope of $R_{tot} T$ vs. $L_f$ in figure 2.7, $2 R_c T$ and $\frac{1}{2} R_{sh}^{sw}$ can be extracted, respectively. If $2 R_c^{sw} T$ is rearranged with the help of equation (2.20) (under the assumption of $L_c \gg L_T^{sw}$), $\rho_c^{sw}$ can be calculated as follows.

$$\rho_c^{sw} = \frac{(2 R_c^{sw} T)^2}{R_{sh}^{sw}} = \frac{(y-intercept)^2}{2 \times \text{slope}}$$

(2.22)

Here, we assume that $R_{sh}^{sw}$ of the channel is the same as that of the active layer under the metal contact. However, there is possibility that they are different. According to TCTLM, $R_{sh}^c$ and $R_c^f W_f$ do not depend on $W_f$, but, in [4], measurement results show that they depend on $W_f$. The observed $W_f$ dependence of $R_{sh}^c$ and $R_c^f W_f$ indicates a non proper current normalization with $W_f$. So a ‘deadzone’ which is a non conductive width from the surface of the fin is introduced. The deadzone width ($x_d$) is modeled as $W_f \rightarrow W_f - 2x_d$ and can be extracted from $R_{sh}^c$. By using deadzone, $R_c^f W_f$ is corrected to be non dependent on $W_f$. With consideration of the deadzone, we need to go a step further by considering deadzone in the channel ($x_{df}$) and in the active layer under the metal contact ($x_{dc}$), which in principle can be different. If $R_{tot} T$ vs. $L_f$ graph in figure 2.7 is considered,
slope is related to increment of $R_{tot}T$. Here, only channel length is changed for each device (the contact is assumed to be the same for all devices). It indicates that $\rho_s$ and $W_f$ in $R_{SW}^c$ from slope of $R_{tot}T$ vs. $L_f$ graph are totally from channel, not from the active layer under metal contact. However, $\rho_s$ and $W_f$ in $R_{sh}^S$ in $R_{SW}^c$T are from the active layer under metal contact. Note that the deadzone can be introduced by $W_f \rightarrow W_f - 2x_d$ where $x_d$ is deadzone width from one side of the fin. $x_d$ is $x_{df}$ and $x_{dc}$ for $R_{sh}^S$ of the channel and $R_{SW}^c$T, respectively. If $x_{df} \neq x_{dc}$ (equivalent to $W_f - x_{df} \neq W_f - x_{dc}$), or $\rho_s$ in channel $\neq \rho_s$ in the active layer under the contact, then $R_{sh}^S$ of channel $\neq R_{sh}^S$ of the active layer under the contact. In this case, equation (2.22) cannot be used and another way is needed to extract $\rho_{SW}^c$.

2.5.1 Method for $\rho_s$ extraction

Let us assume that we are dealing with only $L_c \gg L_{SW}^c$ case. Here is the strategy. We assume that $\rho_s$ in the channel and the active layer under metal contacts are the same. (The case that they are different is explained in Section 5.5.) Then, $\rho_s$ can be extracted from $R_{sh}^S$ and used to extract $\rho_{SW}^c$ in $2R_{SW}^cT$. If equation (2.18) is rearranged and $W_f \rightarrow W_f - 2x_{df}$ is applied, then the following equation comes out.

$$\frac{1}{R_{sh}^S} = \frac{1}{2\rho_s} (W_f - 2x_{df}) \quad (2.23)$$

From equation (2.23), if $1/R_{sh}^S$ vs. $W_f$ is plotted, then $\rho_s$ and $x_{df}$ can be extracted from the slope and y (or x)-intercept of the linear extrapolation. An example of a plot of equation (2.23) is shown in figure 2.8 (a). Therefore, from equation (2.23), the semiconductor resistivity of the channel, $\rho_s$, can be extracted.

2.5.2 Method for $\rho_c$ extraction

Likewise what we have done to extract $\rho_s$, if equation (2.20) is rearranged, the result is as follows.
From equation (2.24), \( \frac{1}{R_{2h}^{SW}} \) and \( 2x_{dc} \) can be extracted from the slope and y (or x)-intercept of the linear extrapolation. An example of a plot of equation (2.24) is in figure 2.8 (b). To extract \( \rho_s^{SW} \) from the slope, we need to assume that \( \rho_s \) for the channel is the same as that for the active layer under the metal. Then \( \rho_s \) which is extracted from \( 1/R_{sh}^{SW} \) vs. \( W_f \) can be used to extract \( \rho_c^{SW} \) from the slope of \( 1/(\sqrt{2}R_c^{SWT})^2 \) vs. \( W_f \).

From the extrapolation of equation (2.23) and equation (2.24), \( \rho_s \) and \( \rho_c^{SW} \) can be extracted, respectively. In addition, \( x_{df} \) and \( x_{dc} \) can be extracted simultaneously with \( \rho_s \) and \( \rho_c^{SW} \). So we can also investigate \( x_{df} \) and \( x_{dc} \) by using these extraction methods. An important point for design is that to use the extraction methods suggested in figure 2.8, \( W_f \) needs to be set as variable and devices with different \( W_f \) are necessary. Because \( R_{sh}^{SW} \) and \( R_c^{SWT} \) are extracted from \( R_{tot}T \) vs. \( L_f \), the total number of devices needs to be \# \( L_f \) splits \( \times \# \) \( W_f \) splits.

2.6 Discussion
To be more familiar with the properties of sidewall contacts, it would be good to compare the sidewall and top contact resistance. Let us consider a TLM structure with conformal metal around fin shown in figure 2.9. For simplicity, the contact resistance can be modeled with parallel connection between top and sidewall contact resistance. In this structure, top and sidewall contact resistance can be represented as follows.

**Top contact resistance**

\[
R_{t}^{c} = \frac{\sqrt{R_{sh}^{t} \rho_{c}^{t}}}{W_{f}} \coth \left( \frac{L_{c}}{L_{T}^{t}} \right) = \frac{1}{W_{f}} \sqrt{\frac{T}{\rho_{s}^{t} \rho_{c}^{t}}} \coth \left( \frac{L_{c}}{\rho_{c}^{t} / \rho_{s}^{t} / T} \right)
\]

**Sidewall contact resistance**

\[
R_{sw}^{c} = \frac{\sqrt{R_{sh}^{sw} \rho_{c}^{sw}}}{2T} \coth \left( \frac{L_{c}}{L_{T}^{sw}} \right) = \frac{1}{2T} \sqrt{\frac{T}{\rho_{s}^{sw} \rho_{c}^{sw}}} \coth \left( \frac{L_{c}}{\rho_{c}^{sw} / \rho_{s}^{sw} / (W_{f} / 2)} \right)
\]

where

\[
R_{sh}^{t} = \frac{\rho_{s}}{T}
\]

\[
L_{T}^{t} = \frac{\rho_{c}^{t}}{R_{sh}^{t}} = \frac{\rho_{c}^{t}}{\rho_{s}^{t} / T}
\]

\[
L_{T}^{sw} = \frac{\rho_{c}^{sw}}{R_{sh}^{sw}} = \frac{\rho_{c}^{sw}}{\sqrt{\rho_{s}^{sw} / (W_{f} / 2)}}
\]

There are two important points that we need to notice. First, if \(L_{c} \gg L_{T}\), \(R_{t}^{c} \propto 1/W_{f}\) and \(R_{sw}^{c} \propto 1/\sqrt{W_{f}}\). If the active layer is grown by epitaxy, it cannot be too thick. So, there is usually no available room to vary \(T\), and \(T\) is fixed. Then \(W_{f}\) is the only variable. If \(W_{f}\) is scaled smaller and
smaller, then \( R_c^t \) increases faster than \( R_c^{SW} \). Also, \( L_T^t \) is not changed as \( W_f \) is scaled. But \( L_T^{SW} \) becomes smaller as \( W_f \) decreases, and it makes easier to be satisfied with \( L_c \gg L_T \) condition. Therefore, \( R_c^{SW} \) is more robust than \( R_c^t \) for \( W_f \) scaling. Next, \( R_c W_f \) and \( R_c^{SW} 2T \) totally depend on properties of top and sidewall contact, respectively. If the current is properly normalized with consideration of the deadzone, the following equations come out from equation (2.25):

\[
R_c^t(W_f - 2x_{dc}) = \sqrt{R_{sh}^t \rho_c^t \coth \left( \frac{L_c}{L_T^t} \right)} = \sqrt{\frac{\rho_s \rho_c^t}{T - x_{dt}}} \coth \left( \frac{L_c}{\sqrt{\rho_c^t}} \right) \quad (2.26)
\]

\[
R_c^{SW} 2(T - x_{dt}) = \sqrt{R_{sh}^{SW} \rho_c^{SW} \coth \left( \frac{L_c}{L_T^{SW}} \right)} = \sqrt{\frac{\rho_s \rho_c^{SW}}{W_f - x_{dc} / 2}} \coth \left( \frac{L_c}{\sqrt{\rho_c^{SW} W_f - 2x_{dc} / 2}} \right) \quad (2.27)
\]

where \( x_{dt} \) is the deadzone depth from the top surface. Note that because depletion due to Fermi level pinning is one of the possible sources of deadzone, there can also be a deadzone at the top surface. From equation (2.26), \( R_c^t(W_f - 2x_{dc}) \) depends on \( \rho_c^t \) and \( x_{dt} \), which are properties of the top contact. Also, from equation (2.27), \( R_c^{SW} 2(T - x_{dt}) \) depends on \( \rho_c^{SW} \) and \( x_{dc} \), which are properties of the sidewall contact.

Finally, there is one comment on extraction method for \( \rho_s \). If \( \frac{T}{W_f / 2} \) is multiplied on each side of equation (2.23), the result is as follows.

\[
\frac{1}{R_{sh}^{SW} W_f / 2} - \frac{T}{R_{sh}^t W_f / 2} = \frac{1}{R_{sh}^t} \left( 1 - \frac{2x_{df}}{W_f} \right) \quad (2.28)
\]

For equation (2.28), if \( \frac{1}{R_{sh}^{SW} W_f / 2} \) vs. \( \frac{1}{W_f} \) is plotted, then \( R_{sh}^t \) and \( x_{df} \) can be extracted from the slope and y-intercept of the linear extrapolation. This seems more physically meaningful, because multiplying \( (W_f / 2)/T \) to \( R_{sh}^{SW} \) is converting \( R_{sh}^{SW} \) to \( R_{sh}^t \). Because \( R_{sh}^t = \frac{\rho_s}{T} \) can be used to extract \( \rho_s \), equation (2.28) is another extraction method for parameters. However, equation (2.28) needs one more modification (multiply \( \frac{T}{W_f / 2} \)) than equation (2.23) does, so equation (2.23) may give more accurate results.
2.7 Summary

In this chapter, we start from basic concept of metal and semiconductor contact and contact resistance. For the top contact, $R_c^T$ is derived by using TLM and extraction method for $R_{sh}^T$ and $R_c^W$ is introduced. Also, two constraints on dimensions of TLM structure for validating assumptions in TLM are evaluated. Next, a structure for sidewall contact is suggested and $R_{cs}^{SW}$ for sidewall contact is derived. Extraction of $2R_c^{SW}T$ and $R_{sh}^{SW}$ is similar to that of TCTLM. Then extraction methods for $\rho_s$ and $\rho_c^{SW}$ are introduced. Finally, properties of $R_c^T$ and $R_c^{SW}$ are compared and another extraction method for $\rho_s$ is suggested. In the following chapter, fabrication steps for SCTLM structures will be described.
CHAPTER 3. Fabrication process

3.1 Introduction

In this chapter, we describe the fabrication process for the structure suggested in Chapter 2 to extract sidewall contact resistivity, $\rho_{cs}$. From now on, this structure is called fin sidewall contact (FSWC) structure. As mentioned in Chapter 2, to extract $R_{cwT}$ and $R_{sh}$, $L_f$ splits are needed. Also, for extraction of $\rho_s$ and $\rho_c$, $W_f$ splits are needed. Therefore, a combination of splits for $L_f$, $W_f$, and $L_c$ are fabricated. To investigate the way to improve $\rho_c$, digital etch and annealing are explored. For digital etch, there are five splits for combinations of several cycles and chemicals, and each sample corresponds to one digital etch split. For annealing, several temperatures with sequential annealing are tested. Fabrication process is designed and done by Dr. Alon Vardi in Prof. Jesús A. del Alamo’s group.

3.2 Process flow

In this section, the detailed process flow for fabrication of FSWC structure is described. Overall process flow is depicted in figure 3.1. Each step is explained in detail as follows.

Step 1. Starting Heterostructure

Details of the starting heterostructure for FSWC structure is shown in figure 3.2. Each layer is grown by molecular beam epitaxy (MBE) from IntelliEPI Inc. The substrate is semi-insulating InP. The buffer is 400 nm intrinsic In$_{0.52}$Al$_{0.48}$As followed by etch stop of 4 nm intrinsic InP.
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<th>Top view</th>
<th>Cross-section view</th>
</tr>
</thead>
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<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>2. Fin writing via electron beam lithography</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td>3. Fin etch by dry etch</td>
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<td><img src="image6.png" alt="Image" /></td>
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<td>4. Digital etch</td>
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<td><img src="image11.png" alt="Image" /></td>
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<tr>
<td>7. FOX protection layer writing via electron beam lithography</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
</tr>
<tr>
<td>8. Mo etch</td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 3.1. Pictorial view of overall process flow.
On top of the InP etch stop, there is a highly Si doped \( n\sim3 \times 10^{19}\text{cm}^{-3} \) \( n^+\text{-In}_{x}\text{Ga}_{1-x}\text{As} \) cap composed of two layers: a 30 nm thick layer with \( x=0.53 \) followed by a 10 nm thick layer with \( x=0.7 \). As mentioned in Chapter 2, to make a good Ohmic contact, a highly doped semiconductor layer is needed at the surface to make a narrow Shottky barrier. Actually, in our starting heterostructure, the only conductive semiconductor layer is the highly doped cap and this is used as the active layer in the FSWC structure.

![Diagram](image.png)

**Figure 3.2.** Starting heterostructure for FSWC structure.

**Step 2. Fin writing via electron beam lithography**

The process starts by cleaving the wafers as received from the grower in five pieces (about 1 cm \( \times \) 1 cm size). They are then cleaned in acetone with ultrasonic for 3 min to remove particles on the surface of the samples. About a 2~3 nm Si\(_3\)N\(_4\) adhesion layer is deposited to facilitate adhesion of hydrogen silsesquioxane (HSQ) through chemical vapor deposition (CVD) in an STS/Multiplex PECVD. High frequency deposition (13.56 MHz on showerhead) is used. For wide area pattern, HSQ does not need an adhesion layer to be patterned on an InGaAs surface, but an adhesion layer is necessary for HSQ for small area or narrow patterns. Results of HSQ adhesion tests with evaporated thin Si layer as an adhesion layer are shown in [12]. Si\(_3\)N\(_4\) is used instead of Si in this study. After adhesion layer deposition, 6% HSQ is spun on samples in spin coater at 3500 rpm for 1 min. Then fin writing is done via electron beam lithography (EBL) using an Elionix ELS-F125. Acceleration voltage of electron beam, writing resolution, and current are 125 keV, 2 nm, and 1 nA, respectively. \( L_{\text{cd}}, L_{\text{f0}}, \) and \( W_{\text{f0}} \) (written value of \( L_{\text{c}}, L_{\text{f}}, \) and \( W_{\text{f}} \) via electron beam lithography, respectively) are shown in table 3.1. In Chapter 5 (after \( p_{\text{ct}}^{\text{sw}} \) is extracted in Chapter 4), whether SCTLM is available or not for these dimensions will be confirmed by using conditions with \( \eta \) that
is derived in Chapter 2 as well as numerical method using HSpice. Because different sized patterns need a different electron charge dose, from dose test of HSQ, a dose for each width of the fin is determined as summarized in table 3.2. After EBL, HSQ is developed with 25% tetramethylammonium hydroxide (TMAH) for 72 sec. Then the samples are rinsed with acetone, methanol and isopropyl alcohol.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Splits [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_c$</td>
<td>500, 750, 1000</td>
</tr>
<tr>
<td>$L_f$</td>
<td>250, 500, 750, 1000, 1250, 1500</td>
</tr>
<tr>
<td>$W_f$</td>
<td>40, 50, 60, 70, 80, 90, 100, 200</td>
</tr>
</tbody>
</table>

Table 3.2. Electron charge dose for each fin width.

<table>
<thead>
<tr>
<th>$W_{f0}$ [nm]</th>
<th>Dose [$\mu$C/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 - 60</td>
<td>6400</td>
</tr>
<tr>
<td>70 - 100</td>
<td>6075</td>
</tr>
<tr>
<td>200</td>
<td>5200</td>
</tr>
</tbody>
</table>

Step 3. Fin etch by dry etch

For the next step, the fin structure is etched through inductively coupled plasma reactive ion etch (ICP RIE) in SAMCO 200iP. After cleaning and conditioning the chamber, InGaAs and InAlAs are etched for 80 sec with BCl$_3$/SiCl$_4$/Ar of gas flow 3/0.53/11 sccm, respectively. This recipe is developed for highly anisotropic InGaAs etch for high aspect ratio vertical structure [13].

Step 4. Digital etch

After the fin etch is done, digital etch is applied for each sample. Digital etch is composed of two steps: self-limited oxidation with oxygen plasma and wet etch with acid solution. Oxidation step is done with oxygen plasma in Asher for 3 min and the applied power is 1000 W. After oxidation steps, wet etch is done for 1 min with the first cycle and 10 sec after the second cycle. Chemicals for wet etch are H$_2$SO$_4$ (H$_2$SO$_4$:H$_2$O=1:1) or HCl (HCl:H$_2$O=1:3). For the H$_2$SO$_4$ solution, right after H$_2$SO$_4$ is mixed with H$_2$O, the solution becomes hot. To avoid unexpected side effect from
heat during digital etch, enough cooling down of solution is necessary. Typically, single cycle of
digital etch removes 1 nm [14]. The purpose of digital etch is removing a surface layer which is
damaged by plasma during fin etch and in this way exposing a higher quality surface. In this study,
to investigate the way to improve $\rho_e^{sw}$, the number of digital etch cycles and two kinds of acids for
wet etch are explored for each sample. Table 3.3 gives the nomenclature of the samples, which
indicates the digital etch splits.

Table 3.3. Summary of digital etch splits and name of samples.

<table>
<thead>
<tr>
<th>Digital etch cycles</th>
<th>1 cycle</th>
<th>2 cycle</th>
<th>3 cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2\text{SO}_4$</td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
</tr>
<tr>
<td>HCl</td>
<td>C1</td>
<td>C2</td>
<td></td>
</tr>
</tbody>
</table>

**Step 5. Mo and W deposition**

After digital etch, 50 nm of Molybdenum (Mo) and 10 nm of Tungsten (W) are sputtered in an
AJA International ATC-1800. Mo and W need to be sputtered right after the samples are wet-
etched, because native oxide is produced by exposing the sample to air yielding a worse contact.
The reason for using W is to prevent Mo from oxidation [15]. Note that HSQ fin mask on top of
InGaAs is not removed. This insures that, after Mo and W deposition, the active layer is only
contacted with Mo on the sidewalls. This is the key point of making sidewall contact without top
contact.

**Step 6. Pad formation**

After Mo and W deposition, pads are formed through lift-off using photo lithography. AZ5214-E,
an image reversal photoresist, is spun on the samples in a spin coater for 30 sec at 3000 rpm. The
samples are pre-baked on a hotplate for 2 min at 80 °C. Then the samples are aligned and exposed
to UV in a Karl Suss MA6 contact aligner, for 9 sec with low vacuum condition. Because the
photoresist needs to be reversed, the samples are baked on a hotplate for 80 sec at 110 °C. Then,
for flood exposure, the samples are exposed to UV again for 90 sec. After this, the photoresist is
developed by using AZ422 for 120 sec. Then 15 nm Ti is deposited followed by 75 nm Au
deposition with electron beam evaporation in a Temescal VES2550. Finally, the pads are formed
through lift-off by dipping the samples in acetone.
Step 7. FOX protection layer writing via electron beam lithography

To isolate devices from each other, Mo and W need to be etched. Because Mo and W under the pads are protected by the Au pad during Mo and W etch, a protection layer for the access line from the pads to the active device is needed. For the protection layer, FOX 16 (high concentration HSQ from Dow Corning) is used. FOX is spun on the samples with 3000 rpm for 1 min in spin coater. Then the pattern for the protection layer is written via EBL in the Elionix ELS-F125. Acceleration voltage, writing resolution, and current are 125 keV, 5 nm, and 10 nA, respectively. 1548 and 1400 μC/cm² are used for electron dose of $L_{f0} = 250$ nm and other $L_{f0}$, respectively. After EBL, FOX is developed with 25% TMAH for 90 sec. In this process, $W_{f0}$ nm in the central portion of the fin should not be covered by FOX, because it is the channel of the FSWC structure, and Mo and W that cover it need to be etched.

Step 8. Mo and W etch

After the FOX protection layer is made, Mo and W are etched with SF₆/O₂ with a gas flow 87/10 sccm, respectively, via electron cyclotron resonance reactive ion etching (ECR RIE) in Plasmaquest Series 11 Model 145. Etching time is 160 sec with around 10 sec overetch. Mo and W on the central portion of the fin are etched and the device is isolated. Actually, the fins are not completely vertical, Mo and W on the sidewall are also etched. Mo and W under the FOX protection layer and the Au pads are not etched. Top-down images taken by scanning electron microscopy (SEM) before and after Mo and W etch are shown in figure 3.3. By comparing figure

![Figure 3.3. Top-down SEM images of central portion of fin (a) before Mo etch, (b) after Mo etch.](image)
3.3 (a) and (b), it is clearly seen that, after Mo and W etch, the exposed semiconductor fin has a width that is narrower than that of the fin covered by Mo and W. Actually, on top of the semiconductor fin, there is an HSQ fin mask. Although the HSQ is etched by SF6, in Chapter 4, through focused ion beam (FIB) image, we confirm that not all HSQ fin mask is etched by Mo and W overetch. Also, the reason of tilted entrance of FOX tunnel at the both ends of the fin (one end of the fin is marked with red circle and arrows in figure 3.3 (a), also seen in figure 3.3 (b)) is because FOX goes back when SEM is zoomed in. The reason for this behavior of the FOX layer is not clear at this moment, but one possible explanation is damaging of FOX because of electron beam. Actually, in figure 3.3 (b), Mo and W part at both ends of the fin should be covered with FOX and supposed not to be inspected via top-down view. But because FOX goes back after zoom in, Mo and W part (marked with red squares in figure 3.3 (b)) is revealed and can be inspected. Top-down SEM images of the final device are shown in figure 3.4 (a) and (b). Also, in figure 3.4 (c), a cartoon for the final FSWC structure is shown.

![Figure 3.4. Top-down SEM images for a device, especially marked for (a) pad and FSWC structure, (b) FOX protection layer and exposed fin (zoom-in image of FSWC structure in (a)), (c) cartoon for the final FSWC structure.](image)

**Step 9. Annealing**

As mentioned at the beginning, annealing is another factor that is investigated to improve $\rho_{c}^{5W}$ in this study. Annealing is done only for sample C1 through rapid-thermal annealing (RTA) in N$_2$ ambient in an Annealsys reactor. Annealing temperatures are 250, 300, 350, and 400 °C, and the sample is sequentially annealed for 3 min at each temperature. At 400 °C, to prevent decomposition of InGaAs, the sample is upside down on a GaAs piece.
3.3 Summary

In this chapter, each step of the process flow for FSWC structure is described. The key point of the process is sputtering Mo and W with HSQ fin mask on top of the active layer. Therefore, there is no top contact, but only sidewall contact between the active layer and Mo, which is the same structure as that suggested in Chapter 2. In the next chapter, measurement results and analysis will be described.
CHAPTER 4. Experimental results and analysis

4.1 Introduction

In this chapter, we describe measurement results and analyze them. First, the measurement method, four probe Kelvin technique, is explained and results of $I-V$ measurements of the FSWC structure as well as $R_{tot}T$ vs. $L_f$ are displayed. Next, the result of extraction of $R_{sh}^{SW}$, $R_{c}^{SW}T$, $\rho_s$, and $\rho_{c}^{SW}$ are given. Then, the impact of digital etch and annealing on $\rho_{c}^{SW}$ is described.

4.2 Measurement results

$I-V$ measurements are done for the FSWC structures which are fabricated in Chapter 2. For this measurement, the four-probe (Kelvin) resistance measurement scheme is used. Because Kelvin resistance measurement scheme measures current and voltage from different probes, the resistance of the cable connecting the probe and test station does not affect the measurements. In figure 4.1, the whole FSWC structure including the access line and the pads with port connections is shown. Among the four ports, one port is used for applying and sweeping voltage, and measuring the current. Another one pair of ports is used for sensing voltage. If symmetry with the axes along the longer and shorter sides of the fin (axis 1 and axis s in figure 4.1, respectively) is considered, there are four possible combinations of applying voltage and sensing current, and they are shown in table 4.1. In figure 4.1, the pads which are touched by port 1 and 3 are connected via metal access lines. Because (if we ignore resistance of metal) every point on the metal access line from port 1 and 3 has the same potential, port 1 and 3 are, effectively, applied to the same end of fin.
Table 4.1 Possible combinations of applying voltage and sensing current (× indicates that the corresponding port is not used for applying or sensing.).

<table>
<thead>
<tr>
<th>I-V Combination</th>
<th>Port 1</th>
<th>Port 2</th>
<th>Port 3</th>
<th>Port 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Apply $V_{app}$ (sweep)</td>
<td>$V = 0$</td>
<td>$I = 0$</td>
<td>$I = 0$</td>
</tr>
<tr>
<td></td>
<td>Sense $I$</td>
<td>$\times$</td>
<td>$V_1$</td>
<td>$V_2$</td>
</tr>
<tr>
<td>2</td>
<td>Apply $V_{app}$ (sweep)</td>
<td>$I = 0$</td>
<td>$I = 0$</td>
<td>$V = 0$</td>
</tr>
<tr>
<td></td>
<td>Sense $I$</td>
<td>$V_2$</td>
<td>$V_1$</td>
<td>$\times$</td>
</tr>
<tr>
<td>3</td>
<td>Apply $I = 0$</td>
<td>$V = 0$</td>
<td>$V_{app}$ (sweep)</td>
<td>$I = 0$</td>
</tr>
<tr>
<td></td>
<td>Sense $V_1$</td>
<td>$\times$</td>
<td>$I$</td>
<td>$V_2$</td>
</tr>
<tr>
<td>4</td>
<td>Apply $I = 0$</td>
<td>$I = 0$</td>
<td>$V_{app}$ (sweep)</td>
<td>$V = 0$</td>
</tr>
<tr>
<td></td>
<td>Sense $V_1$</td>
<td>$V_2$</td>
<td>$I$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>

This means that changing ports 1 and 3 does not affect the result. This argument can also be applied to ports 2 and 4. Therefore, all I-V combinations in table 4.1 should give the same I-V results. I-V measurements are done with Agilent 4155A semiconductor parameter analyzer. The result of I-V measurements for the first I-V combination for one set of $L_{f0}$ devices with $L_{c0}=1000$ nm and $W_{f0}=80$ nm in sample S1 are shown in figure 4.2 (a). The horizontal axis of the graph in figure 4.2 (a) is $V_1-V_2$ which, in principle, is the same as the applied voltage, $V_{app}$. The vertical axis of the graph is the normalized current by the thickness of the active layer ($T=40$ nm). The reason why normalization factor is thickness of the active layer is described in Chapter 2. The result shown in Fig. 4.2(a) makes sense because, as $L_{f0}$ increases, the inverse of slope of the I-V graph, that is
resistance, increases, which indicates that a longer fin has a larger resistance. Each device is measured also for other I-V combinations and resistances are extracted from the inverse of the slope of the I-V graphs. The normalized total resistance ($R_{totT}$) is calculated by averaging the resistance values obtained from the four I-V combinations for one device. $R_{totT}$ of the devices for $L_{c0}=1000 \text{ nm}$ and $W_{f0}=80 \text{ nm}$ of sample S1 are shown in figure 4.2 (b). From figure 2.7, the slope and y-intercept of $R_{totT}$ vs. $L_{f0}$ correspond to $\frac{1}{2} R_{sw}^\text{sh}$ and $2R_c^\text{sw}T$, respectively, as labeled in figure 4.2 (b). In figure 4.2 (b), $R_{totT}$ vs. $L_{f0}$ follows a good linear trend which means that each device has a similar $R_c^\text{sw}$ and an increment of $L_{f0}$ in each device gives a similar increment of channel resistance, $R_{ch}$, which matches well theoretical expectations.

Figure 4.2. (a) The result of I-V measurement with the first I-V combination and (b) $R_{totT}$ vs. $L_{f0}$ for one set of $L_{f0}$ for $L_{c0}=1000 \text{ nm}$ and $W_{f0}=80 \text{ nm}$ in sample S1.

### 4.3 Parameter extraction

In this section, the procedure and the results for extraction of $R_c^\text{sw}$ and $R_{sh}^\text{sw}$ from $R_{totT}$ vs. $L_{f0}$, and extraction of $\rho_s$ and $\rho_c$ from $R_{sh}^\text{sw}$ vs. $W_f$ and $R_c^\text{sw}$ vs. $W_f$, respectively, are described in detail.
4.3.1 $R_{sw}^s$ and $R_{sh}^s$ extraction

Before we extract the slope and y-intercept of $R_{tot}T$ vs. $L_f$, we need to consider that there is a possibility that the real $L_f$ is different from $L_{f0}$. This needs to be checked by SEM. Since it is hard to measure $L_f$ of all devices, to be reasonable, first, $L_f$ of all devices for $L_{co}=750$ nm in each sample are measured to consider sample to sample variations. Then, to figure out section to section variations inside a sample, $L_f$ of devices for $L_{co}=500$ nm and $L_{f0}=250$ nm in sample S1 are measured and compared with $L_f$ of devices for $L_{co}=750$ nm and $L_{f0}=250$ nm in the same sample. The results of the measurements are shown in figure 4.3 and table 4.2.

In figure 4.3 (a), an example of $L_f$ measurement from an SEM image is shown. We notice that the front end of Mo is uneven, so edge of the Mo contact at the top of the fin and the sidewall can be different. Thus, it is hard to measure the exact value of $L_f$. A reasonable estimation is the edge of the Mo contact at the sidewall. In a sample, for fixed $L_{co}$ and $L_{f0}$, the measured $L_f$ for different $W_{j0}$ are averaged. The average values of $L_f$ are shown in figure 4.3 (b), and black lines for $L_{f0}$ are marked to facilitate recognition of the offset of $L_f$ from $L_{f0}$. $L_f - L_{f0}$ is plotted in figure 4.3 (c). Except in cases of $L_{f0} \geq 1000$ nm in C2 which shows negative increase of $L_f - L_{f0}$ and $L_{f0} \geq 1000$ nm of sample S3, $L_f - L_{f0}$ of all samples shows a decreasing trend as $L_{f0}$ becomes longer. This trend can be from the electron dose for FOX layer. Because the electron dose is the same for $L_{f0} \geq 500$ nm, this trend indicates that the longer fins are written more accurately with a lower dose, which matches with intuition. The reason for the exception (cases of $L_{f0} \geq 1000$ mm of samples C2 and S3) is not clear at this moment. Although the electron dose for $L_{f0}=250$ nm is increased as described in Chapter 3, it turns out not to be effective and it needs to be increased more to reduce $L_f - L_{f0}$. However, the samples can be grouped according to $L_f - L_{f0}$: S1, S2, and C1 shows similar $L_f - L_{f0}$. Also, S3 and C2 (for $L_{f0} \leq 750$ nm) have similar $L_f - L_{f0}$ which is (significantly) lower than those of S1, S2, and C1. Because $L_f$ is determined by the FOX protection layer followed by Mo etch and Mo etch is done for all samples simultaneously, these grouping is suspected to come from the EBL conditions used in the exposure of the FOX protection layer. For example, there can be different amount of misalignment for different positions in the sample holder.
in the EBL chuck. Through the grouping, it is revealed that there is a sample to sample variation for $L_f - L_{f0}$. Next step is to verify the section to section variation in a sample. $L_f$, $L_f - L_{f0}$, and standard deviation($\sigma$) for $L_{f0}=250$ nm and $L_{co}=750$ and 500 nm in sample S1 are shown in table 4.2, and those values are close. Therefore, there is no significant section to section variation in a sample. From the results on sample to sample variations and section to section variations in a sample, $L_f$ values which are measured in devices with $L_c=750$ nm can also be used for devices with $L_c=500$ and 1000 nm. The $L_f$ values that are used for $R_{tot}T$ vs. $L_f$ and extraction of $R_{sh}^{sw}$ and $R_{c}^{sw}T$ are summarized in table 4.3.

![SEM image](image.png)

Figure 4.3. (a) An example of SEM image for measuring $L_f$ ($L_{co}=750$ nm, $W_{f0}=100$ nm, and $L_{f0}=250$ nm in sample S1), (b) Measured $L_f$ for samples ($L_{co}=750$ nm), (c) $L_f - L_{f0}$ vs. $L_{f0}$ for each sample ($L_{co}=750$ nm).
Table 4.2. Comparison of $L_f$, $L_f - L_{f0}$, and standard deviation($\sigma$) for $(L_{f0}, L_c0)=$(250, 750), (250, 500) nm in sample S1.

<table>
<thead>
<tr>
<th></th>
<th>$L_f$ [nm]</th>
<th>$L_f - L_{f0}$ [nm]</th>
<th>Standard dev. ($\sigma$) [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{c0}$=750 nm</td>
<td>324</td>
<td>74</td>
<td>7.3</td>
</tr>
<tr>
<td>$L_{c0}$=500 nm</td>
<td>328</td>
<td>78</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Table 4.3. $L_f$ values [nm] that are used for $R_{tot} T$ vs. $L_f$ and extraction of $R_{sh}^{sw}$ and $R_{c}^{sw}$.

<table>
<thead>
<tr>
<th></th>
<th>$L_{f0}$=250 nm</th>
<th>500 nm</th>
<th>750 nm</th>
<th>1000 nm</th>
<th>1250 nm</th>
<th>1500 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>324</td>
<td>550</td>
<td>797</td>
<td>1040</td>
<td>1280</td>
<td>1516</td>
</tr>
<tr>
<td>S2</td>
<td>320</td>
<td>555</td>
<td>790</td>
<td>1043</td>
<td>1282</td>
<td>1521</td>
</tr>
<tr>
<td>S3</td>
<td>298</td>
<td>519</td>
<td>761</td>
<td>1006</td>
<td>1267</td>
<td>1508</td>
</tr>
<tr>
<td>C1</td>
<td>317</td>
<td>554</td>
<td>802</td>
<td>1052</td>
<td>1283</td>
<td>1534</td>
</tr>
<tr>
<td>C2</td>
<td>283</td>
<td>501</td>
<td>751</td>
<td>988</td>
<td>1232</td>
<td>1470</td>
</tr>
</tbody>
</table>

Figure 4.4. (a) $R_{sh}^{SW}$ vs. $W_{f0,S1}$, (b) $R_{sh}^{SW}$ vs. $W_{f0,S1}$ for $L_{c0}$=1000 nm in sample S1.

An example of extracted $R_{sh}^{SW}$ and $R_{c}^{SW} T$ for $L_{c0}$=1000 nm in sample S1 is shown in figure 4.4. The horizontal axis of figure 4.4 is logarithmic scale of $W_{f0,S1}$ which is $W_{f0} - 2$ nm. 2 nm comes from 1 nm reduction from each side for the single-cycle digital etch. From equation (2.18), because $R_{sh}^{SW} = \frac{\rho_s}{W_f/2}$, $R_{sh}^{SW}$ needs to be proportional to $W_f^{-1}$. However, as in figure 4.4 (a), the data
points deviate from the red line which slope is $-1$. This may be from differences between measured $W_f$ and $W_{f0,c1}$, but because it gives good curved trend, it is highly suspected it comes from a shift of $W_{f0,c1}$, which is the deadzone introduced in Chapter 2.

### 4.3.2 $\rho_s$ and $\rho_c$ extraction

We first need to decide whether or not a deadzone is introduced in $R_c^{SW}T$. From equation (2.20), $R_c^{SW}T$ needs to be proportional to $W_f^{-1/2}$ under the assumption of $L_c \gg L_T$ where $L_T^{SW} = \sqrt{\rho_c^{SW}/R_{sh}^{SW}}$. In figure 4.4 (b), overall trend of $R_c^{SW}T$ deviates from the red line whose slope is $-1/2$. (all data points in figure 4.4 (b) satisfy the condition, $L_c \gg L_T^{SW}$ as will be described later.) So we also need to consider deadzone in the active layer under the contact. Another reasoning is possible. The deadzone is considered to come from plasma damage during fin etch and subsequent Fermi level pinning [4]. The whole fin can be considered to have suffered from plasma damage and Fermi level pinning. So if deadzone appears in the channel, then deadzone may exist in the other part along the fin. Because, through deviation of $R_c^{SW}$ from $W_f^{-1}$ trend, we noticed that deadzone appears in the channel, it is reasonable to expect a deadzone in the active layer under the contact. (But there is possibility for deposited metal to reduce the deadzone through passivation.)

![Figure 4.5](image-url)  
Figure 4.5. Parallel translation of line for extrapolation in (a) $1/R_{sh}^{SW}$ vs. $W_f$ and (b) $1/(\sqrt{2}R_c^{SW}T)^2$ vs. $W_f$.  

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If the deadzone is introduced, as mentioned in Chapter 2, \( W_{f0} \) needs to become \( W_{f0} - 2x_d \) where \( x_d \) is the deadzone width from one side of the fin. If width reduction from digital etch is included, \( R^{sw}_{sh} \) and \( R^{sw}_{cT} \) can be derived with the help of equations (2.18) and (2.20) and they are as follows.

\[
R^{sw}_{sh} = \frac{\rho_s}{(W_{f0}-2x_{DE}-2x_{df})/2} \tag{4.1}
\]

\[
R^{sw}_{cT} = \sqrt{R^{sw}_{sh} \cdot \rho_s^{sw}} = \frac{\rho_s \rho_c^{sw}}{\sqrt{(W_{f0}-2x_{DE}-2x_{dc})/2}} \tag{4.2}
\]

where \( x_{DE} \) is width reduction due to digital etch from one side of the fin, and \( x_{df} \) and \( x_{dc} \) are the deadzone for the channel and the active layer under the contact, respectively. Note that \( x_{DE} \) is different for each S1, S2, and S3 because different numbers of cycles of digital etch are applied for each of them and so for C1 and C2. Equation (4.2) is approximated equation for \( R^{sw}_{cT} \) under the assumption of \( L_c >> L_{cT} \). If the methods for \( \rho_s \) and \( \rho_c^{sw} \) extraction introduced in Chapter 2 are used, equation (2.23) and (2.24) are modified as follows.

\[
\frac{1}{R^{sw}_{sh}} = \frac{1}{2\rho_s} \left( W_{f0} - 2x_{DE} - 2x_{df} \right) \tag{4.3}
\]

\[
\frac{1}{(\sqrt{R^{sw}_{cT}})^2} = \frac{1}{\rho_s \rho_c^{sw}} \left( W_{f0} - 2x_{DE} - 2x_{dc} \right) \tag{4.4}
\]

From equation (4.3), through the slope of the linear fit of \( 1/R^{sw}_{sh} \) vs. \( W_{f0} \), \( \rho_s \) of the channel can be extracted. Also, from equation (4.4), from the slope of the linear fit of \( 1/(\sqrt{R^{sw}_{cT}})^2 \) vs. \( W_{f0} \), \( \rho_s \rho_c^{sw} \) can be extracted. If \( \rho_s \) of the channel is assumed to be same as that of the active layer under the contact, \( \rho_c^{sw} \) can be extracted from \( \rho_s \rho_c^{sw} \) with the help of extracted \( \rho_s \) of the channel from equation (4.3). However, like \( L_{f0}, W_{f0} - 2x_{DE} \) needs to be verified under SEM. As with \( L_f \), the measured fin width, \( W_f \), needs to replace \( W_{f0} - 2x_{DE} \) in equations (4.3) and (4.4). In section 4.3.1, because both slope and y-intercept are needed, the exact values of \( L_f \) are required. However, because only slopes of equation (4.3) and (4.4) are needed to extract \( \rho_s \) and \( \rho_c^{sw} \), it is sufficient to verify that all \( W_f \) are shifted from \( W_{f0} \) by the same amount instead of needing to measure the exact values of \( W_f \). This principle can be easily explained in the way that parallel translation of a line does not change slope, as shown in figure 4.5. In figure 4.5, although \( x_{df}' \neq x_{df} \) and \( x_{dc}' \neq x_{dc} \).
\( p' = \rho_s \) and \( \rho_s \rho_c^{SW} = \rho_s \rho_c^{SW} \) under a transformation \( W_f \rightarrow W_f - \alpha \), where \( \alpha \) is a constant.

Actually, measuring exact values of \( W_f \) needs elaboration and this will be discussed later.

Figure 4.6. (a) An example of SEM image for measuring \( W_{fb} \) (\( L_{c0} = 750 \text{ nm}, W_{f0} = 100 \text{ nm}, \) and \( L_{f0} = 250 \text{ nm} \)). (b) Measured \( W_{fb} \) for the samples (\( L_{c0} = 750 \text{ nm} \)). (c) \( W_{fb} - W_{f0} \) vs. \( W_{f0} \) for each sample (\( L_{c0} = 750 \text{ nm} \)).

Table 4.4 \( W_{fb} - W_{f0} \) and standard deviation (\( \sigma \)).

<table>
<thead>
<tr>
<th>Sample</th>
<th>( W_{fb} - W_{f0} ) [nm]</th>
<th>Standard dev. (( \sigma )) [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>S2</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>S3</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>C1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>C2</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
To verify whether or not $W_f - W_{f0}$ for each $W_{f0}$ in the fixed $L_{c0}$ is similar, the width of the fin via top-down SEM image is measured. An example of a fin width measurement is shown in figure 4.6 (a). Because the actual cross-section of fin is not vertical but gradually widens from top to bottom, the fin width which is measured by top-down view SEM image corresponds to the (nearly) bottom width of the fin. So, actually, the measured width of fin is not the width of the active layer. Nevertheless, it is reasonable to consider that the bottom width has a certain geometrical relationship with the width of the active layer, and that this geometrical relationship is satisfied for all fins in a sample. Therefore, for the fins of all $W_{f0}$ in a certain $L_{c0}$ in a sample, if $W_{fb} - W_{f0}$ where $W_{fb}$ is the bottom width of the fin is similar, then $W_f - W_{f0}$ can be considered to be similar. Example images of cross-section of the fin in the channel and under the contact are in Section 5.6. Basically, fin cross-section can be modeled as a trapezoid and the geometrical relationship in the trapezoid can connect $W_{fb}$ and $W_f$. Detail explanation is in Section 5.6.

The results of $W_{fb}$ measurement are in figure 4.6 and table 4.4. In figure 4.6 (a), an example of $W_{fb}$ measurement with SEM image is shown. At the edge of the fin, there is white band which comes from electron charging. In the inspection of the fins for the same $L_{c0}$, all settings for the
SEM conditions are the same (astigmatism correction and focus are little bit adjusted for each fins but should be similar), and the time taking the images for each fin is also almost same. So charging can be considered to be similar for each inspection of the fins for the same $L_{c0}$. In figure 4.6 (b), the measured $W_{fb}$ for fins with $L_{c0}=750$ nm in each sample is shown. For example, every data points in S2 deviates about 10 nm from $W_{f0}$ (horizontal black lines). To be specific, in figure 4.6 (c) and table 4.4, $W_{fb} - W_{f0}$ for fins with $L_{c0}=750$ nm in each sample is shown. In table 4.4, the standard deviation for $W_{fb} - W_{f0}$ is about 1 to 2 nm, which means that $W_{fb} - W_{f0}$ for each $W_{f0}$ in the same $L_{c0}$ are closely clustered. It can then be concluded that $W_{fb} - W_{f0}$ is similar in each sample. This means that $W_f - W_{f0}$ for each $W_{f0}$ is also similar and linear trend lines for the fit of $1/R_{sh}^{sw}$ vs. $W_f$ and $1/(\sqrt{2} R_{c}^{sw} T)^2$ vs. $W_f$ for real $W_f$ can be considered as parallel translations of that for $W_{f0}$. Therefore, $W_{f0}$ (or $W_{f0} - 2x_{DE}$) can be used to extract $\rho_s$ and $\rho_c^{sw}$. In other words, equation (4.3) and (4.4) can be used for extraction of $\rho_s$ and $\rho_c^{sw}$ without replacing $W_{f0} - 2x_{DE}$ by the measured $W_f$.

Plots of equation (4.3) and (4.4) for $L_{c0}=1000$ nm in sample S1 are shown in figure 4.7. Because a single-cycle digital etch is done in sample S1, 1 nm is used for $x_{DE}$. Extracted values for $\rho_s$ and $\rho_c^{sw}$ from the slopes of figure 4.7 (a) and (b), respectively, are in the table 4.5. Note that when $\rho_c^{sw}$ is extracted from the slope of figure 4.7 (b), the extracted value of $\rho_s$ from the slope of figure 4.7 (a) is used.

Before we go further, the $L_c >> L_{c}^{sw}$ condition which is used to approximate the cotangent hyperbolic term in the original expression of $R_c^{sw}$ (equation (2.19)) to 1 in the derivation of equations (2.20) or (4.2) needs to be verified. In figure 4.8 (a), the right half of FSWC structure is shown and $L_c$ is defined. This is a top-down view of the middle of the active layer. To measure $L_c$, because there is FOX protection layer on top of Mo contact, it needs to be removed by buffered oxide etch (BOE). As shown in figure 4.8 (b), after BOE treatment, when the FOX protection layer is removed, the Mo contact is revealed. Also, it is depicted that the length which can be measured is actually $L_c - T_{Mo,sw}$ where $T_{Mo,sw}$ is thickness of Mo on the sidewall of the active layer. Therefore, to get $L_c$, $T_{Mo,sw}$ needs to be added to the measured length. From the cross-section picture of focused ion beam (FIB) shown in figure 4.8 (e), $T_{Mo,sw}=27.5$ nm is measured. Between top Mo layer and the active layer, there is HSQ fin mask. Because BOE etch HSQ which is SiO$_2$,
top Mo layer is detached and found to be gone away in some devices. In figure 4.8 (c), the top Mo layer is partially left on the fin and that on the access line is gone away. In figure 4.8, (d), the whole top Mo layer is gone. Also, in figure 4.8 (e) and (f), there are SEM pictures for Mo overshoot and undercut, respectively. Because Mo overshoot makes $L_c$ longer, it helps the device to satisfy $L_c \gg L_{SW}^0$ condition. But Mo undercut ($=l_{Mo, uc}$) reduces $L_c$, we need to take this case into account as the shortest $L_c$ case. Because measuring $l_{Mo, uc}$ is impossible if there is a top Mo layer on the fin like figure 4.8 (a) and (b), only the case of figure 4.8 (c) can be used to measure $l_{Mo, uc}$.

Figure 4.8. (a) Definition of $L_c$ with the right half of FSWC structure, (b), (c), (d) three different cases after removing FOX protection layer, (e) thickness of Mo on the sidewall ($(L_{co}, L_{fo}, W_{fo}) = (1000, 1500, 80) \text{ nm}$ in sample S1) (f) Mo overshoot, (g) Mo undercut.
Before the measurement, one thing needs to be considered. Because wet etch with BOE destroys the devices, it is important to use damaged or dummy devices for measuring $L_c$. There are dummy devices whose dimension is $L_{c0} = 500 \text{ nm}$, $W_{f0} = 2000 \text{ nm}$, and $L_{f0} = 250-1500 \text{ nm}$. Also, sample S3 is broken. Therefore, we can first measure $L_c$ for many devices with different dimension to verify that there is no variation of $L_c - T_{Mo,sw}$ in a sample by using sample S3. If so, we can measure $L_c - T_{Mo,sw}$ in dummy devices for each sample and use them as representative value of $L_c - T_{Mo,sw}$ for each sample. To properly evaluate the shortest $L_c$ for the tightest case for $L_c \gg L_T^{sw}$, the following strategy is used. First, measure $L_c - T_{Mo,sw}$ without consideration of $l_{Mo,uc}$ in sample S3 and figure out that whether there is variation in a sample or not. Next, if there is no variation in a sample, measure $L_c - T_{Mo,sw}$ from dummy devices in each sample (without consideration of $l_{Mo,uc}$). Next, measure $l_{Mo,uc}$. Finally, estimate the shortest $L_c$ with $L_c - T_{Mo,sw}$ and $l_{Mo,uc}$.

In table 4.6, the result of $\Delta L_c = L_c - L_{c0}$ is summarized. $L_c$ is calculated by $(L_c - T_{Mo,sw}) + T_{Mo,sw}$. For one $W_{f0}$, several devices from different $L_{f0}$ are measured and all measured $L_c - T_{Mo,sw}$ values for a certain $L_{c0}$ is averaged. In table 4.6, the average of $\Delta L_c$ for dummy devices is very close to that of whole sample S3. Thus, dummy devices can be used to predict the average of $\Delta L_c$ for each sample. In table 4.7, $\Delta L_c$ from dummy devices of each sample is summarized. Here, we can notice that $\Delta L_c$ of S2 and C1 are similar and those of S3 and C2 are similar. This result is similar with grouping in $L_f$ (except S1), and it is suspected to come from misalignment of FOX protection layer, which affects both $L_f$ and $L_c$.

For the next step, $l_{Mo,uc}$ is measured. Because dummy devices in sample S2 are found to be as figure 4.8 (d) after applying BOE, $l_{Mo,uc}$ is measured from them. We assume that there is no sample to sample variation for $l_{Mo,uc}$ and the value measured in sample S2 can be used in the other samples. The reason is that Mo etch is done for all samples simultaneously. Note that, for $L_c$, because EBL writes pattern sample by sample, there can be sample to sample variations. There are four sidewall contacts in a device and $l_{Mo,uc}$ can be measured from all of the four sidewall contacts. $l_{Mo,uc}$ is measured from dummy devices with $L_{f0} = 500, 750, 1000 \text{ nm}$, and the result is in table 4.8. Finally, the worst case of $\Delta L_c$, which considers Mo undercut, for each sample is calculated by
\[ \Delta L_{c,\text{worst}} = \Delta L_c - l_{\text{Mo,uc}} \] and the results are summarized in table 4.8. Data used in figure 4.7 is confirmed to satisfy with \( L_c \gg L_T^{SW} \).

One thing needs to be checked is that we used an average value instead of the maximum absolute value for \( \Delta L_c \) and \( l_{\text{Mo,uc}} \). The reason is that the maximum absolute value of \( \Delta L_c \) is quite random, so it is impossible for dummy devices to be representative of the maximum absolute of \( \Delta L_c \) in a sample. Actually, to find out maximum absolute values of \( \Delta L_c \) and \( l_{\text{Mo,uc}} \), it is required to measure \( \Delta L_c \) and \( l_{\text{Mo,uc}} \) of all devices and for this, we need to wet-etch all devices. Also, taking average values of \( \Delta L_c \) and \( l_{\text{Mo,uc}} \) is expected to be reasonable because they are considered to already include large portion of devices. For example, if we think about devices with no Mo undercut, using average values of \( \Delta L_c \) satisfies \( L_c \gg L_T^{SW} \) for only half of devices. But because we subtract \( l_{\text{Mo,uc}} \), \( \Delta L_c - l_{\text{Mo,uc}} \) satisfies \( L_c \gg L_T^{SW} \) for more than half of devices with no Mo undercut.

With the \( \Delta L_{c,\text{worst}} \) values for each sample, \( L_c \gg L_T^{SW} \) condition is evaluated. Only data points which satisfy the condition, \( L_{c,\text{worst}} = (L_{c0} + \Delta L_{c,\text{worst}}) \geq 1.5 \times L_T^{SW} \), are used to extract \( \rho_c^{SW} \). Values of \( L_{c,\text{worst}} \) for each sample are shown in table 4.8. Here, \( L_{c,\text{worst}}/L_T^{SW} \geq 1.5 \) makes \( \coth(L_c/L_T^{SW}) \leq 1.105 \) in approximation from equation (2.19) to (2.20). It means that we allowed error which is equal or lesser than 10% for \( R_c^{SW}T \) (Bur for extraction of \( \rho_c^{SW} \), up to 10% error in \( R_c^{SW}T \) can affect \( 1/(\sqrt{2}R_c^{SW}T) \) to be underestimated up to 18%. However, as \( W_f \) decreases, \( L_T^{SW} \) decreases. So narrow \( W_f \) devices have small error in \( R_c^{SW}T \). Because \( \rho_c^{SW} \) is extracted from the
slope of a linear fit, we expect overall averaging effect from data of all $W_f$ and relatively small error in $R^{SW}_c T$ from wide $W_f$ may mitigate the effect of relatively large error in $R^{SW}_c T$ from $W_f=200$ nm during $\rho^{SW}_c$ extraction.)

Table 4.7 Result of $L_c$ measurement for each sample with dummy devices.

<table>
<thead>
<tr>
<th>Sample</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta L_c$ [nm]</td>
<td>-36</td>
<td>-55</td>
<td>-69</td>
<td>-52</td>
<td>-69</td>
</tr>
</tbody>
</table>

Table 4.8 Result of $l_{Mo,uc}$ measurement and $\Delta L_{c,worst} = \Delta L_c - l_{Mo,uc}$ for each sample.

<table>
<thead>
<tr>
<th>$l_{Mo,uc}$ [nm]</th>
<th>Average [nm]</th>
<th>Standard deviation [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>46</td>
<td>23</td>
</tr>
<tr>
<td>Sample</td>
<td>S1</td>
<td>S2</td>
</tr>
<tr>
<td>$\Delta L_{c,worst}$ = $\Delta L_c - l_{Mo,uc}$ [nm]</td>
<td>-82</td>
<td>-101</td>
</tr>
</tbody>
</table>

4.4 Effect of digital etch and annealing

In this section, we investigate the result of applying digital etch and annealing. Each digital etch split corresponds to a different sample, and annealing is applied to sample C1. Extraction of $\rho_s$ and $\rho^{SW}_c$ for each digital etch and annealing split follows the method that is described in Section 4.3. Note that the measured values of $L_f$, the rationale to use $W_f 0 = X_{DE}$ instead of measured $W_f$, and verification of $L_c >> L_T$ which are described in section 4.3, can be applied in all digital etch and annealing splits.

4.4.1 Effect of digital etch

$\rho_s$ and $\rho^{SW}_c$ of each sample are the average values of the extracted $\rho_s$ and $\rho^{SW}_c$ from each $L_{co}=500$, 750, and 1000 nm. Because devices of $L_{co}=500$ nm of sample S1 and C2 do not satisfy the
condition $L_c \gg L_T^{SW}$, $\rho_c^{SW}$ from these cases are not included in the average $\rho_c^{SW}$. The results of $\rho_s$ and $\rho_c^{SW}$ for each sample are shown in figure 4.9. First, in figure 4.8 (a), as the number of digital etch cycles increases, $\rho_s$ initially a little bit increases for both Sulfuric and Hydrochlorine acid, and is not changed much from the second to the third cycle for Sulfuric acid. It is not clear at this moment why $\rho_s$ changes as the number of digital etch cycles increases.

![Figure 4.9. (a) $\rho_s$ and (b) $\rho_c^{SW}$ for digital etch spits (S and C indicates Sulfuric acid and Hydrochloric acid, respectively.).](image)

In any case, the change of $\rho_s$ as the number of digital etch cycles increases is small. Next, in figure 4.8 (b), as the number of digital etch cycles increases, $\rho_c^{SW}$ initially decreases a little bit for Hydrochlorine acid, but, for Sulfuric acid, initially decreases and does not change much from the second to the third cycle. The initial decrease of $\rho_c^{SW}$ can be attributed to removal of the surface which is damaged by fin etch plasma. It is not clear at this moment why $\rho_c^{SW}$ does not continue to decrease from the second to the third cycle for Sulfuric acid. One possible reason is that the damaged region is completely removed after the second cycle of digital etch with Sulfuric acid. This needs to be verified through other experiments with more digital etch cycles. Therefore, two cycles of digital etch improve $\rho_c^{SW}$ while sacrificing a little bit of an increase in $\rho_s$.

### 4.4.2 Effect of annealing
Process details of sequential annealing are described in Chapter 3. Annealing is done for sample C1, and devices with \( L_{c0} = 750 \) and 1000 nm are measured. The extracted values of \( \rho_s \) and \( \rho_{c}^{sw} \) from \( L_{c0} = 750 \) and 1000 nm are averaged, then plotted in figure 4.9. In figure 4.9 (a), as the annealing temperature increases, \( \rho_s \) decreases until 300 °C and increases after 300 °C. The overall change of \( \rho_s \) is not very significant. The overall trend of \( \rho_{c}^{sw} \) is to decrease down to \( 3.7 \pm 0.01 \, \Omega \cdot \mu \text{m}^2 \) at 400 °C, which is about 1.9 times improvement from the starting \( \rho_{c}^{sw} = 6.9 \pm 0.05 \, \Omega \cdot \mu \text{m}^2 \). This trend is similar to the change of Mo/n⁺-InGaAs top surface contact resistance as the annealing temperature increases in [16]. One difference is that the top surface contact resistance in [16] decreases until 350 °C and increases after 350 °C.

The best result \( \rho_{c}^{sw} = 3.7 \pm 0.01 \, \Omega \cdot \mu \text{m}^2 \) at 400 °C annealing is about 5.4 times that of \( \rho_{c}^{sw} = 0.69 \pm 0.3 \, \Omega \cdot \mu \text{m}^2 \) for Mo/In0.53Ga0.47As top contact (InGaAs layer is 20 nm thick, Si-doped, and \( N_D = 1 \times 10^{19} \, \text{cm}^3 \)) reported in [16]. So further investigation for reducing sidewall contact resistivity is needed. Therefore, sequential annealing of the contact improves \( \rho_{c}^{sw} \) while sacrificing a little bit of an increase in \( \rho_s \).

![Graph](image-url)

Figure 4.10. Change of (a) \( \rho_s \) and (b) \( \rho_{c}^{sw} \) as annealing temperature increases.
4.5 Summary

In this chapter, the measured $R_{tot}$ is displayed and $R_{sh}', R_{c}^{sw} T$, $\rho_s$, and $\rho_c^{sw}$ are extracted. Also, the results of $\rho_c^{sw}$ for digital etch and annealing splits are shown. From sample C1, a lowest $\rho_c^{sw}$ of $3.7 \pm 0.01 \Omega \cdot \mu m^2$ is obtained after $400 ^\circ C$ annealing. This is about 1.9 times improvement over non-annealed $\rho_c^{sw} = 6.9 \pm 0.05 \Omega \cdot \mu m^2$ and about 5.4 times larger than reported top contact resistivity $\rho_c = 0.69 \pm 0.3 \Omega \cdot \mu m^2$. As a summary of the effect of digital etch and annealing, two cycles of digital etch or sequential annealing up to $400 ^\circ C$ improves $\rho_c^{sw}$ with little sacrifice in $\rho_s$. The combination of digital etch and annealing may show more improvement of $\rho_c^{sw}$. In the next chapter, several issues are discussed, including validity evaluation of SCTLM for the dimensions of the fabricated devices by using the condition of $\eta$ (equation (2.17)) and numerical simulation with HSpice.
CHAPTER 5. Discussions

5.1 Introduction

In Chapter 4, the extraction of \( \rho_s \) and \( \rho_c^{SW} \) has been described for the fabricated FSWC devices using the SCTLM structures introduced in Chapter 2. However, there are some assumptions and issues that need to be checked. First, the validity of SCTLM, which is mentioned in Chapter 2, needs to be verified. Second, negative x-intercept in \( R_c^{SW}T \) vs. \( W_f - 2x_{DE} \) is discussed. Third, because the FSWC structure fabricated in Chapter 3 has not only the fin but also access lines connected to the fin, the effect of the access lines needs to be considered. Fourth, the assumption that \( \rho_s \) of channel is considered to be the same as that of the active layer under the contact needs to be checked. Finally, \( W_f \) measurement and deadzone extraction is discussed.

5.2 Validity of SCTLM

In Chapter 2, two assumptions for the TLM approximation were described and equation (2.17), which indicates necessary condition for TLM, was derived. Equation (2.17) which is an inequality condition for the ratio of contact resistance and semiconductor resistance under the contact per unit area, \( \eta = \rho_c^e / \rho_s T \), is related to the dimension of contact, the contact resistivity, and the semiconductor resistivity. However, as mentioned in Chapter 2, because there can be more assumptions for TLM and more conditions that needs to be satisfied (this is the reason why equation (2.17) is not sufficient but necessary condition), a numerical evaluation is needed.
Before we start to explore numerical evaluation, the results of $\rho_s$ and $\rho_c^{SW}$ can be quickly checked with equation (2.17). The SCTLM version of equation (2.17) is as follows:

$$0.81 \leq \eta^{SW} \ll \left( \frac{L_c}{W_f/2} \right)^2$$

(5.1)

where $\eta^{SW} = \rho_c^{SW} / \left( \rho_s \left( \frac{W_f}{2} \right) \right)$ ($T \rightarrow W_f/2$ is applied.). In equation (5.1), because the left inequality is derived under the assumption of the right inequality (which is equivalent to $L_c \gg L_T^{SW}$) and every data satisfies $L_c \gg L_T^{SW}$, only the left inequality needs to be evaluated. If the left inequality in equation (5.1) is rearranged, the result is as follows:

$$W_f \leq \frac{\frac{2}{0.81} \rho_c^{SW}}{\rho_s}$$

(5.2)

The tightest condition for $W_f$ is from the smallest ratio of $\rho_c^{SW}$ and $\rho_s$ and this comes from $L_{c0}=1000$ nm in sample S2, which gives $\rho_c^{SW}/\rho_s=1.4 \mu$m. Therefore, equation (5.2) gives $W_f \leq$
3.5 μm. Because devices with $W_f \leq 200$ nm are used, the fabricated FSWC devices easily satisfy equation (5.2).

Coming back to the numerical evaluation, the SCTLM is modeled with a one-dimensional series of resistors for the active layer, which assumes that current in the active layer is uniform and flows perpendicular to the cross-section of the active layer. However, in reality, because the direction of current flow at the contact is perpendicular to that in the channel, for current to go into the contact in the shortest possible way, there is current crowding at the contact edge as well as in the channel. This means that current flow in the channel is not uniform, and, near the contact, the current has a component which is not perpendicular to the cross-section of the active layer. Therefore, the active layer needs to be modeled with a two-dimensional resistor mesh.

SCTLM and two-dimensional resistor mesh model for the FSWC structure are shown in figure 5.1. The metal resistance is ignored. MATLAB is used to generate HSpice code for the resistor network of SCTLM and the two-dimensional mesh. (MATLAB code can be considered to generate HSpice code with input structure.) Originally, the MATLAB code for generating HSpice code was written by Wenjie Lu in Professor Jesus del Alamo’s group and the author (Dongsung Choi) used the code with input structure of SCTLM and the two-dimensional mesh shown in figure 5.1. By using HSpice, current is calculated for the given voltage, and the total resistance ($R_{tot}$) from contact to contact is calculated. Enough number of nodes in the mesh is used to get accurate results. Because the widest fin deviate the most from SCTLM, $W_f = 200$ nm cases for all different $L_{c_0}$ of digital etch and annealing splits are tested. For simplicity, we use $W_f = W_f_0$ in simulation. If SCTLM is proved to be valid for $W_f = W_f_0$, then we can conclude that SCTLM is valid for $W_f \leq W_f_0$, which automatically includes the case of considering deadzone, $W_f - 2x_d$. Used $\rho_s$ and $\rho_e^{sw}$ values in the simulations are summarized in table 5.1. Table 4.3 is used for $L_f$ input and $L_{c,worst} (= L_{c_0} + \Delta L_{c,worst}$, where $\Delta L_{c,worst}$ is in table 4.8) is used for $L_c$ input in HSpice simulation.

From the results, all cases of $L_{c_0}$ in digital etch and annealing splits show lower than 1% difference of $R_{tot}$ between SCTLM and the two-dimensional mesh, which is acceptable. If the metal resistance is measured and used in the SCTLM and two-dimensional mesh, more accurate calculation can be done.
Table 5.1. Used ($\rho_s, \rho_c^{sw}$) [\(\Omega \cdot \mu m, \Omega \cdot \mu m^2\)] values in simulation (\(\times\) indicates \(L_c \gg L_T^{sw}\) violation.).

<table>
<thead>
<tr>
<th>Digital etch splits</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{co}=500) nm</td>
<td>(\times)</td>
<td>2.3, 5.4</td>
<td>2.2, 6.3</td>
<td>2.3, 6.7</td>
<td>(\times)</td>
</tr>
<tr>
<td>(L_{co}=750) nm</td>
<td>2.0, 10.5</td>
<td>2.3, 8.5</td>
<td>2.6, 4.0</td>
<td>2.3, 6.8</td>
<td>2.6, 6.2</td>
</tr>
<tr>
<td>(L_{co}=1000) nm</td>
<td>2.2, 7.2</td>
<td>2.7, 3.7</td>
<td>2.2, 6.5</td>
<td>2.3, 6.9</td>
<td>2.6, 6.0</td>
</tr>
<tr>
<td>Annealing splits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(L_{co}=750) nm</td>
<td>250 °C</td>
<td>300 °C</td>
<td>350 °C</td>
<td>400 °C</td>
<td></td>
</tr>
<tr>
<td>(L_{co}=1000) nm</td>
<td>2.3, 5.3</td>
<td>2.2, 5.7</td>
<td>2.3, 4.6</td>
<td>2.4, 3.7</td>
<td></td>
</tr>
</tbody>
</table>

5.3 Negative x-intercept of trend line in \(R_c^{sw}T\) vs. \(W_{f0} - 2x_{DE}\)

During the extraction process of \(\rho_c^{sw}\) from \(R_c^{sw}T\) vs. \(W_{f0} - 2x_{DE}\), \(x_{dc}\) for some splits turns out to be negative, as shown in table 5.2 (negative values are marked with bold and italic). (However, all \(x_{df}\) extracted from \(R_{sh}^{sw}\) vs. \(W_{f0} - 2x_{DE}\) are positive values.) In this thesis, because \(W_{f0} - 2x_{DE}\) are not measured values, only the slopes (1/2\(\rho_s\) and 1/\(\rho_s\rho_c^{sw}\)) are taken into account and the x-intercepts (2\(x_{df}\) and 2\(x_{dc}\)) are ignored. However, negative x-intercepts (\(x_{dc}\)) may show how much the deadzone extraction is sensitive. Especially, somehow, extraction through intercept seems more unstable compared with that through the slope. This can be found in the fact that the linearity of \(1/(\sqrt{2}R_c^{sw}T)^2\) vs. \(W_{f0} - 2x_{DE}\) (figure 4.7 (b)) is worse than that of \(1/R_{sh}^{sw}\) vs. \(W_{f0} - 2x_{DE}\) (figure 4.7 (a)). This indicates that \(R_c^{sw}T\) extracted from y-intercept in \(R_{tot}T\) vs. \(L_f\) is more unstable than \(R_{sh}^{sw}\) extracted from slope in \(R_{tot}T\) vs. \(L_f\). This may give instability to \(x_{dc}\) which is obtained through two sequential intercept extractions (\(x_{dc}\) is from x-intercept of \(R_c^{sw}T\) vs. \(W_f\) and \(R_c^{sw}T\) is from y-intercept of \(R_{tot}\) vs. \(L_f\).) The reason why extraction through the intercept seems more unstable than that through the slope is not clear at this moment.
Table 5.2. Extracted $x_{dc}$ [nm] with $R^T_{csw}$ vs. $W_{f0} - 2x_{DE}$ ($\times$ indicates $L_c >> L^T_{csw}$ violation. Negative values are marked with bold and italic. Note that because $W_{f0} - 2x_{DE}$ is not measured value of $W_f$, $x_{dc}$ in this table is not real deadzone width.).

<table>
<thead>
<tr>
<th>Digital etch splits</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{co}$=500 nm</td>
<td>$\times$</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>$\times$</td>
</tr>
<tr>
<td>$L_{co}$=750 nm</td>
<td>$-10$</td>
<td>$-2$</td>
<td>13</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>$L_{co}$=1000 nm</td>
<td>9</td>
<td>17</td>
<td>10</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annealing splits</th>
<th>250 °C</th>
<th>300 °C</th>
<th>350 °C</th>
<th>400 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{co}$=750 nm</td>
<td>1</td>
<td>$-3$</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>$L_{co}$=1000 nm</td>
<td>1</td>
<td>$-1$</td>
<td>$-3$</td>
<td>18</td>
</tr>
</tbody>
</table>

5.4 The effect of the access line

The fin and access lines in the EBL mask for etching the active layer are shown in figure 5.2 (a). In figure 5.2 (b), the boundary of the fin and the access line with the metal sidewall contact is shown. The desired path for current is going into the metal contact before the access line. But as depicted in figure 5.2 (b), current can go into the metal contact through the access line too. If the amount of this current component is large, it can result in an error in the measurement which it includes not only the fin but also the access line. Therefore, it is important to make sure that the metal contact on the fin is long enough so that only little amount of current is allowed to pass the boundary of the fin and the access line. As one possible criteria, $L_c >> L^T_{csw}$ can be considered as a condition for checking that most of the current goes into the metal contact before the access line. Actually, all the data used here already satisfies $L_c >> L^T_{csw}$ in the approximation of $R^T_{csw}$ formula. As a result, the effect of the access line should be negligible for the data used here.

There can be two alternative architectures for FSWC structure, shown in figure 5.3. In figure 5.3, major change of architecture is inserting oxide between the fin and the access line to prevent the current from passing the boundary of the fin and the access line. Because the inserted oxide decouples channel and access line, short $L_{co}$ contact can be studied with those architectures.
Figure 5.2. (a) The fin and the access line in EBL mask for etching the active layer, (b) the boundary of the fin and the access line with metal sidewall contact, (a) and (b) are cross-section at the middle of the active layer.

Figure 5.3. Two architectures are suggested to remove current flowing into the access line from the fin before going into the metal contact. (a) Oxide is inserted between the fin and the access line. (b) another architecture allowing current over-spayring.

In figure 5.3 (a), there is no room for current over-spayring mentioned in Chapter 2, so $L_c \gg L_f^{ow}$ which is equivalent to the right side of the equation (5.1) does not need to be satisfied.
For the original $R_c^{SW}$ (equation (2.19)) to be approximated to equation (4.2), $L_c \gg L_T^{SW}$ is still needed. But the advantage of this architecture allows for another extreme, $L_c \ll L_T^{SW}$, to be explored. If $L_c \ll L_T^{SW}$ is satisfied, cotangent hyperbolic term in equation (2.19) becomes $1/(\frac{L_c}{L_T^{SW}})$ ($x \ll 1 \rightarrow \coth(x) \equiv 1/x$ is used.) and $R_c^{SW}T$ becomes as follows.

$$R_c^{SW}T \equiv \sqrt{R_{sh}^{SW}} \cdot \frac{\rho_c^{SW} L_T^{SW}}{L_c} = \frac{\rho_c^{SW}}{L_c}$$  \hspace{1cm} (5.3)

where $L_T^{SW} = \sqrt{\frac{\rho_c^{SW}}{R_{sh}^{SW}}}$ is used (TCTLM case for $L_c \ll L_T^{SW}$ is in [9]). Equation (5.3) indicates that when $L_c \ll L_T^{SW}$, $R_c^{SW}T$ becomes dependent on $L_c$. The another architecture which allows current over-spreading in figure 5.3 (b) is also possible. Because there is room for current over-spreading, $L_c \gg L_T^{SW}$ which is equivalent to the right side of the equation (5.1) needs to be satisfied. Detail fabrication steps for two suggested architectures have not considered yet, and need to be developed.

### 5.5 The assumption about $\rho_s$ for $\rho_c^{SW}$ extraction

In the extraction of $\rho_c^{SW}$, $\rho_s$ in the channel (extracted from the slope of $R_{sh}^{SW}$ vs. $W_{f0} - 2x_{DE}$) is assumed to be same as that in the active layer under the contact ($\rho_s$ in $R_c^{SW}T$). However, in [17], the semiconductor sheet resistance (which is $\rho_s/T$ for TCTLM) in the channel and the active layer under the contact turn out to be different in the cases of alloyed Au-Ge-Ni contacts on n-type epitaxial GaAs layer and sintered Al metallization on a shallow Sb ion-implanted layer on a p-type Si wafer. The result of a $\rho_s$ difference in alloyed Au-Ge-Ni contacts on n-type epitaxial GaAs layer is regarded as the evidence of alloying modification of epitaxial layer under the contact. Because in the FSWC structure, it is possible for $\rho_s$ in channel and the active layer under the contact to be different (especially in the annealing splits), assuming different $\rho_s$ in channel and the active layer under the contact can yield a more accurate extraction. However, in the current splits here, there is no way to extract $\rho_s$ in the active layer under the contact. In [17], to solve the set of equations with one more variable which is $\rho_s$ in the active layer under the contact, an additional measurement, the ‘contact end resistance’ measurement (CERM), is performed. Therefore, to distinguish $\rho_s$ in
the active layer under the contact from that in the channel, an additional measurement is needed
and the FSWC structure needs to be modified for that measurement.

As an example, CERM can also be applied to the SCTLM. Before details about CERM for
SCTLM are described, main equations in [17] is rewritten with conventions in this thesis. In figure
5.4 (a), the device for TCTLM with CERM is shown with definition of dimensions. In TCTLM,
the resistance, \( R_{1}^{t} \), between two contact (cont1 and cont2) with distance, \( L_{ch} \), can be represented
as follows.

\[
R_{1}^{t} = R_{ch}^{t} + 2R_{c}^{t} = \frac{R_{sh, ch}^{t}}{w} L_{ch} + 2R_{c}^{t}
\]

(5.4)

where \( R_{sh, ch}^{t} (= \rho_{s, ch}/T) \) and \( \rho_{s, ch} \) are semiconductor sheet resistance and semiconductor
resistivity of the channel, respectively. Also, \( R_{c}^{t} \) is represented as follows.

\[
R_{c}^{t} = \frac{\sqrt{R_{sh, cont}^{t} \rho_{c}^{t}}}{w} \coth \left( \frac{L_{c}}{L_{c}^{t} w} \right)
\]

(5.5)

where \( L_{c}^{t} = \frac{\rho_{c}^{t}}{R_{sh, cont}^{t}} \), and \( R_{sh, cont}^{t} (= \rho_{s, cont}/T) \) and \( \rho_{s, cont} \) are semiconductor sheet
resistance and semiconductor resistivity of the active layer under the contact, respectively.
Equation (5.4) and (5.5) are similar with equation (2.9) and (2.7), respectively, but semiconductor
sheet resistance for the channel and the active layer under contact are distinguished as \( R_{sh, ch}^{t} \) and
\( R_{sh, cont}^{t} \), respectively. To decouple \( \rho_{c}^{t} \) and \( R_{sh, cont}^{t} \), additional measurement, CERM, is needed.
Basically, in figure 5.4 (a), the contact end resistance (\( R_{E}^{t} \)) is measured by applying current
between two contacts, cont1 and cont2, and measuring voltage between cont2 and cont3 (one of
two contacts used for applying current and an opposite outside contact). Then \( R_{E}^{t} \) is calculated by
dividing measured voltage by applied current. From [17], \( R_{E}^{t} \) can be represented with TLM
parameters and it is as follows.

\[
R_{E}^{t} = \frac{1}{w} \frac{\sqrt{R_{sh, cont}^{t} \rho_{c}^{t}}}{\sinh(L_{c}/L_{c}^{t})} = \frac{\rho_{c}^{t}}{L_{c}^{t} w} \cdot \frac{1}{\sinh(L_{c}/L_{c}^{t})}
\]

(5.6)
Figure 5.4. (a) Scheme for the contact end resistor measurement (CERM) for TCTLM (reproduced from [17] and modified by the author) (b) scheme 1, (c) scheme 2, and (d) scheme 3 of the modified FSWC for CERM for SCTLM (Nothing is connected to both ends of the fin, and extra contacts at the ends of the fin are just for symmetry (to let current feel perfect symmetry) and not used.).
From equation (5.5) and (5.6), the ratio of $R'_C$ and $R'_E$ is as follow.

$$\frac{R'_C}{R'_E} = \cosh \left( \frac{L}{L_T} \right)$$

(5.7)

Because $R'_C W$ is extracted and $R'_E$ is measured, from equation (5.7), $L_T$ can be calculated. Then from equation (5.6), $\rho'_C$ can be extracted. Also, by using equation for $L_T = \sqrt{\rho'_C / R_{sh,cont}}$, $R_{sh}$ (or $\rho_{s,cont}$) can be calculated. In [17], there is another way to measure $R'_E$ is discussed and the method is as follows.

$$R'_E = \frac{1}{2} (R'_1 + R'_2 - R'_3)$$

(5.8)

where $R'_1$ and $R'_2$ are resistances measured for cont2&cont3 and cont1&cont3, respectively.

This CERM scheme can be used also in the modified FSWC structure shown in figure 5.4 (b). The difference compared with original FSWC structure is adding one more contact at the middle of the fin. Here, $R_{3w}$ is used for $R_{tot}$. Actually, $R_{3w}$ can be also used for $R_{tot}$ as in figure 5.4 (c). This scheme can be considered as making fin longer and adding one more contact at the end of the fin. Both schemes are essentially the same structure and this architecture can be fabricated with the method of making gate without gate oxide in finFET fabrication. The scheme in figure 5.4 (b) is symmetric for measuring $R_{tot}$ because measurement is done between cont1 and cont3. However, because there is a contact at the middle of the fin and the deadzone in the active layer under the contact is considered to be different from that in the channel, there is discontinuity of the deadzone in the channel. The scheme in figure 5.4 (c) is asymmetric for measuring $R_{tot}$ because measurement is done between cont1 and cont2, and the end of cont1 is connected to access line and cont2 is at the middle of the fin. However, this scheme is not suffered from discontinuity of the deadzone in the channel. Because discontinuity of the deadzone is critical to the model, the modified FSWC structure in figure 5.4 (c) is considered to be better than that in figure 5.4 (b). In figure 5.4 (d), there is the ultimate scheme which does not have discontinuity of deadzone as well as is symmetric for $R_{tot}$ measurement. In this architecture, access line is connected to cont1, 2, and 3. Nothing is connected to both ends of the fin, and extra contacts at the ends of the fin are just for symmetry (to let current feel perfect symmetry) and not used. The SCTLM counter component of TCTLM is obtained by $W \rightarrow T$ and $T \rightarrow W_f/2$. The procedure to extract $\rho_{s, ch}$, $\rho_{s, cont}$, and $\rho_{c}^{sw}$
is as follows. First, $R_{1}^{SW}T$ and $R_{E}^{SW}$ are measured from the structure in figure 5.4 (d). Next, $R_{sh}^{SW}$ and $R_{E}^{SW}T$ are extracted from the slope and the y-intercept of the linear extrapolation of $R_{1}^{SW}T$ vs. $L_f$, respectively. SCTLM version of equation (5.7) is as following.

$$R_{c}^{SW} = R_{E}^{SW} \cosh \left( \frac{l_c}{L_{SW}^{c}} \right) = R_{E}^{SW} \cosh \left( \frac{l_c}{\rho_{c}^{SW} W_f / \rho_{s,cont} (z^2)} \right)$$  \hspace{1cm} (5.9)$$

where $L_{SW}^{c} = \sqrt{\frac{\rho_{c}^{SW}}{\rho_{s,cont} (z^2)}}$ is used. If deadzone is taken account, then the following three equations can be derived.

$$\frac{1}{R_{sh}^{SW}} = \frac{2}{\rho_{s,ch}} \left( W_f - 2x_{df} \right)$$  \hspace{1cm} (5.10)$$

$$\frac{1}{(\sqrt{2} R_{c}^{SW})^2} = \frac{1}{\rho_{s,cont} \rho_{c}^{SW}} (W_f - 2x_{dc})$$  \hspace{1cm} (5.11)$$

$$\left( \frac{l_c}{\cosh^{-1} \left( \frac{R_{E}^{sw}}{\rho_{c}^{SW} R_{E}^{SW}} \right)} \right)^2 = \frac{1}{2} \rho_{s,cont}^{SW} (W_f - 2x_{dc})$$  \hspace{1cm} (5.12)$$

where $x_{df}$ and $x_{dc}$ are deadzone in the channel and the active layer under the contact, respectively. $\rho_{s,ch}$ is extracted from the slope of equation (5.10). $\rho_{s,cont} \cdot \rho_{c}^{SW}$ and $\rho_{s,cont} / \rho_{c}^{SW}$ are obtained from the slopes of equation (5.11) and (5.12). By using them, $\rho_{s,cont}$ and $\rho_{c}^{SW}$ can be extracted. Therefore, by modifying FSWC structure and including additional measurement of $R_{E}^{SW}$, $\rho_s$ in the channel and in the active layer under the contact do not need to be assumed to be the same, and through distinguishing $\rho_{s,cont}$ and $\rho_{s,ch}$, more accurate $\rho_{c}^{SW}$ can be obtained.

5.6 $W_f$ measurement and deadzone extraction

In the data analysis, instead of measuring the exact $W_f$, it is observed that the shift of $W_f$ from $W_{f0}$ is similar for all devices in the same $L_{co}$, and by using slope invariant property of parallel
translation of linear trend line, $\rho_s$ and $\rho_{SW}$ are extracted from the slopes of $1/R_{SW}^h$ vs. $W_{f_0} - 2x_{DE}$ and $1/(\sqrt{2}R_{SW}^h) vs. W_{f_0} - 2x_{DE}$, respectively. However, because the $y$ (or $x$)-intercept is changed in the parallel translation and the amount of shift of $W_f$ from $W_{f_0}$ is not measured, $x_{df}$ and $x_{dc}$ can not be extracted. Therefore, to extract $x_{df}$ and $x_{dc}$ from equation (4.3) and (4.4), $W_f$ needs to be measured to replace $W_{f_0} - 2x_{DE}$.

First of all, whether or not $W_f$ of the channel and contact are the same needs to be verified. In figure 5.5 (a) and (b), cross-sections of the fin in the channel and the contact are shown, respectively. They are cut by focused ion beam (FIB). The fin shown in figure 5.5 (a) and (b) has $L_{c0}=1000$ nm, $W_{f_0}=80$ nm, and $L_{f0}=1500$ nm. In figure 5.5 (a), top width of the active layer (InGaAs) is about 82.5 nm which is close to $W_{f_0}$. However, in figure 5.5 (b), top width of the active layer is about 66.7 nm which is far below from $W_{f_0}$. When Mo on the channel is overetched, SF$_6$ also etches HSQ which is essentially the same as SiO$_2$. But as HSQ is etched, not only the height but also the width of HSQ is reduced. Although InGaAs is not considered to be etched by SF$_6$, it is suspected that because of physical bombardment with SF$_6$, the InGaAs layer is damaged and removed. Also, compared with figure 5.5 (a), the fin profile in figure 5.5 (b) is less vertical. Since the sidewall of the fin in figure 5.5 (a) is not perfectly vertical, after Mo on the sidewall is gone during overetch, InGaAs and InAlAs sidewalls are damaged and become more tilted. From a comparison of the cross-sections of the fin, it is revealed that $W_{f, ch} \neq W_{f, cont}$, where $W_{f, ch}$ and $W_{f, cont}$ are the fin widths in the channel and under the contact, respectively.

Therefore, the strategy for data extraction can be set as follows. Because $W_{f, ch}$ and $W_{f, cont}$ are needed for $1/R_{SW}^h$ vs. $W_{f, ch}$ and $1/(\sqrt{2}R_{SW}^h)$ vs. $W_{f, cont}$, respectively, both need to be measured separately. First, $W_{f, cont}$ is very close to $W_{f_0}$. So inspection of cross-section of fins with $W_{f_0}=40$ and 200 nm for certain $L_{c0}$ and $L_{f0}$ is needed, and average of $W_{f, cont} - W_{f_0}$ is taken and used for other fins to estimate $W_{f, cont}$. Actually, it is the best to make statistics with lots of samples, but because FIB takes long time (about 30 min – 1 hr) to cut one fin, an appropriate number of cuts needs to be determined.

Next, because the channel fin can be inspected by SEM, linking top-down SEM image to the cross-section image can be useful.
Figure 5.5. For the fin of $L_{c0}=1000$ nm, $W_{f0}=80$ nm, and $L_{f0}=1500$ nm in sample S1, (a) FIB image of cross-section of the fin under the contact, (b) in the channel, (c) top-down SEM image, (d) different fin with top-down SEM image with high-efficiency secondary electron detector, (e) with in-lens detector, (f) parameter definition for calculating fin width at the middle of the InGaAs layer, left figure is modeling of top-down SEM picture for the fin shown in (c).

Figure 5.5 (c) shows top-down SEM image of the fin in figure 5.5 (b) before FIB is done. Note that there are white-black-white narrow bands from one edge of the fin marked with red lines in figure 5.5 (c). The widths between the bands are measured as shown in figure 5.5 (c) and the width
values (78, 88 nm) are marked in the cross-section image in figure 5.5 (b) (width of 66.7 nm is considered to be at boundary of HSQ and InGaAs in figure 5.5 (b). The 66.7 nm dimension in figure 5.5 (b) is also considered to be similar to the 61 nm dimension in figure 5.5 (c)). From this comparison, it can be known that there are two white bands near the edge, and the widths between the white bands from both sides of the fin (=61 and 78 nm) can be used to estimate the width at some height of the fin in the cross-section image. Because white ‘band’ (instead of line) indicates charging, better SEM image with carefully adjusted conditions (acceleration voltage and current) was taken to verify the existence of a boundary inside the fin. In figure 5.5 (d) and (e), in white colored box, there is a black line which is indicated by white arrow between the lightly charged white bands. Figure 5.5 (d) and (e) are taken by high-efficiency secondary electron detector and in-lens detector, respectively. The fin in figure 5.5 (d) and (e) is different from that in figure 4.14 (a) – (c). What the black line is is not clear at this moment, but it is suspected to be the boundary between the HSQ and InGaAs layer. Therefore, measuring the width between the two black lines from both edges can be an estimation of \( W_{f, ch} \). If it is better to select the width at the middle height of the active layer as \( W_{f, ch} \), it can be calculated with parameters defined in figure 5.5 (f). In figure 5.5 (f), \( H \) is expected to be similar for all devices, because all devices are fabricated simultaneously for fin etch and Mo etch. \( H \) can be measured from FIB image, and \( W_{ft} \) and \( W_{fb} \) can be measured by top-down SEM image. The thickness of InGaAs layer is defined by \( T (=40 \text{ nm}) \). The width of the middle of InGaAs layer can be calculated as follows:

\[
W_{f, ch} = \frac{T/2}{H} \cdot W_{fb} + \frac{H-T/2}{H} \cdot W_{ft} \tag{5.13}
\]

By properly estimating \( W_{f, ch} \) and \( W_{f, cont} \), \( x_{df} \) and \( x_{dc} \) can be extracted from \( 1/R_{sh}^{SW} \) vs. \( W_{f, ch} \) and \( 1/(\sqrt{2}R_{c}^{SW}T)^2 \) vs. \( W_{f, cont} \). This is not done in this study and suggested for the future research with extraction of deadzone.

**5.7 Summary**

In this chapter, several issues about the validity of SCTLM, negative x-intercept of trend line in \( R_{c}^{SW}T \) vs. \( W_{f0} - 2x_{DE} \), the effect of the access line, the assumption about \( \rho_s \) for \( \rho_c^{SW} \) extraction,
and $W_f$ measurement and deadzone extraction are discussed. The next chapter summarizes this thesis and gives suggestions for possible future research topics.
CHAPTER 6. Conclusions and suggestions

6.1 Conclusions

In this thesis, a theoretical model and fabrication steps for studying sidewall Ohmic contact have been developed. The developed methodologies were applied to Mo/n'-InGaAs sidewall contacts, and the effect of digital etch and annealing on $\rho_{c}^{SW}$ were explored to investigate the way to improve $\rho_{c}^{SW}$. Key conclusions are as follows.

1. Two assumptions for TCTLM were explored. To make the assumptions valid, equation (2.17) needs to be satisfied. Through equation (2.17), it can be noticed that whether or not TCTLM is valid depends on the combinations of ratios among the dimensions of contact structure (such as $L_c$, $W$, and $T$) and resistivities ($\rho_{c}^{L}$ and $\rho_{s}$). But those two assumptions are not a complete set and there can be more assumptions which may give more conditions. Therefore, to verify validity of TCTLM, other than using the analytic equations, numerical simulation with HSpice are needed. For example, a comparison of the simulation results from resistive network for TCTLM and two-dimensional resistive mesh can help to verify the validity of TCTLM on a certain structure dimensions and resistivities. In addition, the derived conditions for the assumptions of TCTLM and methodology of using HSpice can be applied to general TLM.

2. SCTLM was developed for the suggested FSWC structure. In SCTLM, $W_f$ is a variable and special care for the range of $W_f$ is needed to insure validity of SCTLM. For example, equation (5.1) gives restriction on $W_f$. As mentioned, to fully evaluate validity of SCTLM, a comparison between SCTLM and two-dimensional resistor mesh through numerical simulation is required. Interestingly, SCTLM has similarity to TCTLM, and $W \rightarrow T$ and $T \rightarrow W_f/2$ converts $R_{c}^{L}$ to $R_{c}^{SW}$.
3. A method for the extraction of $\rho_s$ of the channel and $\rho_{SW}^c$ from $I-V$ measurements of the FSWC structure were developed and described in Section 2.5. The reason for using a linear extrapolation to extract $\rho_s$ and $\rho_{SW}^c$ from $R_{s_sh}$ and $R_{c_sw}^T$ is because the existence of a deadzone needs to be considered. Since $\rho_{s,cont}$ ($=\rho_s$ of the active layer under the contact) cannot be extracted from this experiment, $\rho_{s,cont}$ ($=\rho_s$ of the channel) is assumed to be same as $\rho_{s,cont}$ and used to extract $\rho_{SW}^c$. To deal with $\rho_{s,ch}$ and $\rho_{s,cont}$ separately, the method suggested in Section 5.5 can be used.

4. Fab process for the FSWC structure was developed. The key step is leaving HSQ fin mask after fin etch and depositing Mo and W contact. In this structure, the active layer only contacts with Mo through sidewall.

5. With SCTLM and the fabricated FSWC structure, $\rho_{SW}^c$ was extracted. To investigate the way to improve $\rho_{SW}^c$, the effect of digital etch and annealing on $\rho_{SW}^c$ was evaluated. Digital etch splits were not annealed and annealing experiment was done with sample C1 (single-cycle digital etch with HCl). The lowest $\rho_{SW}^c$ of $3.7 \ \Omega \cdot \mu m^2$ is obtained at 400 °C annealing, which is about 1.9 times improvement of non-annealed $\rho_{SW}^c=6.9 \ \Omega \cdot \mu m^2$. Through the evaluation of the effect of digital etch and annealing on $\rho_{SW}^c$, it is concluded that two cycles of digital etch or sequential annealing up to 400 °C improves $\rho_{SW}^c$ with sacrificing a little increase of $\rho_s$.

6.2 Suggestions for future work

In this section, future works are suggested to continue or improve this study.

1. **Deadzone**: As continuing this research, fin width of the channel ($W_{f,ch}$) and the contact ($W_{f,cont}$) can be measured as discussed in Section 5.6. By using them, the deadzone of the channel ($x_{df}$) and the active layer under the contact ($x_{dc}$) can be extracted. This study will reveal the behavior of $x_{df}$ and $x_{dc}$ when digital etch or annealing is applied. Note that because it is proved in Section 4.3.2 that all $W_f$ can be considered to shift in the same amount, shift of $W_f$ directly corresponds to the x-intercept, $2x_d: \Delta W_f/2 = \Delta x_d$. Thus, accurate measurement or estimation of $W_f$ is needed for accurate extraction of deadzone.
2. **More digital etch and annealing splits**: Because there are a few digital etch splits (three for Sulfuric acid and two for Hydrochlorine acid), it is hard to find the overall trend of $\rho_{\text{SW}}$ as the number of digital etch increases. Also, because $\rho_{\text{SW}}$ has decreasing trend until maximum annealing temperature in this thesis, there is no information about the minimum $\rho_{\text{SW}}$ that can be reduced by annealing. Therefore, by fabricating more digital etch splits and applying higher annealing temperature, a clearer overall trend of $\rho_{\text{SW}}$ can be obtained. There are some cautions for this topic. Because digital etch does not etch HSQ, it makes undercut of InGaAs under HSQ. So many cycles of digital etch can produce large undercut and it can prevent Mo from being completely attached on sidewall of InGaAs right under HSQ during metal sputtering. It means that a new architecture may be needed to explore more digital etch cycles. Also, because As in InGaAs can be dissociated at high temperature, capping with GaAs on the sample for increasing As pressure is needed.

3. **Further reduction of $\rho_{\text{SW}}^*:** As mentioned in Section 4.4.2, the best result in this thesis is about 5.4 times larger than reported top contact resistivity. So further reduction of $\rho_{\text{SW}}^*$ is needed. Annealing with higher temperature or more digital etch can be tried. Also, careful treatment of sidewall surface, such as optimization of fin etch recipe for sidewall condition, may be helpful. But basic understanding for sidewall contact would be needed to make huge improvement.

4. **The effect of the access line**: The architecture suggested in Section 5.4 to remove the effect of the access line can be developed and implemented.

5. **$\rho_{s,\text{cont}} \neq \rho_{s,\text{ch}}$:** To extract (more) accurate $\rho_{\text{SW}}^*$, new method to separately extract $\rho_{s,\text{cont}}$ and $\rho_{s,\text{ch}}$, and corresponding new FSWC architecture are needed. The contact end resistance measurement method and architecture discussed in Section 5.5 can be used. Also, this method is necessary to explore contact resistance of alloyed contacts.

6. **Sidewall contact reliability**: Sidewall surface is damaged by plasma during fin etch. Also, the thickness of the contact metal on the sidewall is thinner than that on the top surface. So sidewall contact is expected to be weak compared with top contact. For example, upper limit of compliance current of the sidewall contact can be lower than that of the top contact. Therefore, compliance current for the sidewall contact can be measured and compared with that of the top contact.

7. **Vertical nanowire sidewall contact**: Sidewall contact research can also be done in nanowire structure. In the case of vertical nanowire made by dry etch (top-down), sidewall contact is
expected to be worse than top contact due to plasma damage of surface during dry etch. (Also, it is interesting to figure out the difference in contact quality between top and sidewall contact in grown vertical nanowire (bottom-up).) Fabrication of the vertical nanowire sidewall contact (VNWC) structure is very similar to that of the fin sidewall contact (FSWC) structure: do not remove HSQ nanowire mask and sputter metal on the nanowire. One advantage is that many cycles of digital etch can be explored in VNWC structure, which is not allowed in the FSWC structure. The reason is as follows. As in the fin case, digital etch makes undercut of the active layer right under the HSQ mask. However, if the contact length is long enough, then most of current goes into the semiconductor far from the top of the nanowire. Therefore, it does not cause a problem that the contact right under the HSQ is poor because of undercut.

8. Sidewall contact with p-type semiconductor: Because circuit technology is based on CMOS, contact to p-type semiconductor is also important. Measuring $\rho_{SW}$ and exploring the way to improve it for the sidewall contact with p-type semiconductor is an interesting topic. All fabrication steps developed in this thesis are available for p-type semiconductor, but recipes for each step need to be changed. Possible p-type semiconductor is InGaSb, which can be considered as the counter part of InGaAs in III-V compound semiconductor.

9. Validity conditions of one-dimensional TLM: In Chapter 2, two validity conditions of one-dimensional TLM are explored. For TCTLM, those conditions are about conditions among $L_c$, $T$, $W$, $\rho_c$, and $\rho_s$. However, there is one more dimension, distance between contacts (= channel length). Therefore, looking for validity condition of one dimensional TLM for channel length can be an interesting topic. Also, there may be more assumptions in TLM and more validity conditions may be derived.

10. Two-dimensional effect in wide fin: As mentioned in Section 5.2, if $W_f$ becomes too wide, then SCTLM becomes not valid. This effect, wide fin effect (WFE), is roughly predicted in Section 2.4. Basically, if $W_f$ becomes very wide, most of current may not use whole width of the fin and the effective fin width is expected to be narrower than the physical fin width. WFE can be explored with two dimensional resistance mesh model with HSpice explained in Section 5.2. Also, there are other ways which do not use resistance mesh and HSpice. For considering two-dimensional current distribution in wide fin, the following previous research can be helpful. In [18], two-dimensional
current distribution under the contact is numerically solved for a top contact. In [19], current distribution in thin film resistor is analytically solved by using conformal mapping.
Bibliography


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