MIT Libraries | DSpace@MIT

MIT Open Access Articles

Contact-independent measurement of electrical Conductance of a Thin Film with a Nanoscale Sensor

The MIT Faculty has made this article openly available. ***Please share*** how this access benefits you. Your story matters.

Citation: Mentzel, Tamar S., Kenneth MacLean, and Marc A. Kastner. "Contact-Independent Measurement of Electrical Conductance of a Thin Film with a Nanoscale Sensor." Nano Letters 11.10 (2011): 4102-4106.

As Published: http://dx.doi.org/10.1021/nl201650u

Publisher: American Chemical Society (ACS)

Persistent URL: http://hdl.handle.net/1721.1/74000

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

Terms of Use: Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.

Massachusetts Institute of Technology

Contact-independent measurement of electrical conductance of a thin film with a nanoscale sensor

Tamar S. Mentzel,* Kenneth MacLean, and Marc A. Kastner

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

E-mail: tamarm@mit.edu

Abstract

Contact effects are a common impediment to electrical measurements throughout the fields of nanoelectronics, organic electronics and the emerging field of graphene electronics. We demonstrate a novel method of measuring electrical conductance in a thin film of amorphous germanium that is insensitive to contact effects. The measurement is based on the capacitive coupling of a nanoscale metal-oxide-semiconductor field-effect transistor (MOSFET) to the thin film so that the MOSFET senses charge diffusion in the film. We tune the contact resistance between the film and contact electrodes and show that our measurement is unaffected. With the MOSFET, we measure the temperature- and field-dependence of the conductance of the amorphous germanium, which fit to a model of variable-range hopping. The device structure enables both a contact-independent and a conventional, contact-dependent measurement, which makes it possible to discern the effect of the contacts in the latter measurement. This measurement method can be used for reliable electrical characterization of new materials and to determine the effect of contacts on conventional electron transport measurements, thus guiding the choice of a non-invasive contact material.

*To whom correspondence should be addressed

The measurement of electrical conductance is one of the most important probes of solid-state systems; however, contact effects routinely interfere with reliable measurements. Throughout nanoelectronics, unstable contacts and large contact resistances arise because of the reduced contact area. Decreased channel lengths cause the contact resistance to dominate the overall resistance.[1] In graphene electronics, the metal-graphene contact resistance has been a barrier to achieving high-performance graphene transistors.[2] In organic electronics, the contact material has been found to alter the morphology of the organic molecules,[3] to penetrate into the molecules,[4,5] to form Schottky barriers irrespective of work function,[6] and to be thermally and mechanically unstable.[7] Electrical resistance of organic monolayers can vary by four orders of magnitude depending on the choice of contact material and the method of contact.[4,8,9] As the charge mobility increases in novel organic materials, contact effects become more pronounced.[8] Moreover, Schottky barriers and diffusion of contact metal, particularly at high temperatures, have long been obstacles to the characterization of semiconductor films. A barrier to solving contact problems is that it can be difficult to discern the effect of the contacts when measuring a new material.[2,4,10] A common technique to eliminate contact resistance from an electrical conductance measurement is a four-point probe measurement; however, these probes can interfere with current flow in nanoscale films or damage soft, organic materials.

In this Letter, we demonstrate a contact-independent measurement of electrical conducance in a thin film of amorphous germanium with a nanoscale metal-oxide-semiconductor field-effect transistor (MOSFET). The nanoscale MOSFET senses charge diffusion in the amorphous germanium film via capacitive coupling to the film instead of direct physical contact. When the gate of a MOSFET is sufficiently narrow ($\lesssim$100 nm), a one-dimensional inversion channel forms, which has a conductance that varies in response to electrostatic fluctuations in the environment. When the MOSFET is placed nearby the amorphous germanium film, the conductance of the MOSFET varies as charge diffuses in the film. From the time dependence of the conductance of the MOSFET, we extract a quantitative measure of the conductance of the amorphous germanium film. We perform this measurement in the presence of both Ohmic and blocking contacts on the a-Ge film,

and find that our measurement is insensitive to contact effects. This technique is used to measure the temperature- and field-dependence of the conductance, both of which fit to a model of variable-range hopping. The density of states and localization length of the film are extracted from the fits. Moreover, we measure conductance as low as 10^{-19} S when applying a bias voltage of only 1 V to the film. The ability to measure such a small conductance could advance our understanding of various highly resistive materials such as high dielectric constant materials used in nanoelectronics. By comparing our contact-independent measurement to a conventional measurement of current in the film, we discern the role of the contacts in the conventional current measurment. This measurement technique can be used for reliable electrical characterization of new materials and to guide the choice of a non-invasive contact material, which could accelerate the application of new materials in electronic devices.

The device structure is displayed in Figure 1. We fabricate an *n*-channel silicon MOSFET on a p-type silicon substrate using standard CMOS techniques. The gate of the MOSFET tapers to a width of ≈60 nm at its narrowest region. A thin film of amorphous germanium that is 200 nm wide and 50 nm thick is patterned 100 nm away from the narrow portion of the gate. The film overlaps a pair of gold electrodes that are separated by 1 μm. By holding the device in a storage vessel for a prolonged period of time before measurement, an oxide is expected to have formed at the interface between the amorphous germanium and the gold electrodes.

We first investigate the nature of the contacts between the amorphous germanium and the gold electrodes. We apply a dc bias voltage V_{aGe} across the amorphous germanium film and measure the current I_{aGe}, as displayed in Figure 2(d). We find that the IV characteristic is non-Ohmic, and that current is immeasurable for $|V_{aGe}| < 5V$. The oxide at the interface between the gold electrodes and the amorphous germanium film introduces a large contact resistance, which dominates the overall resistance at low bias voltages. With a high enough bias volage, $|V_{aGe}| > 5V$, the contact resistance decreases and the conductance of the film can be measured with a conventional current measurement, as found previously by Osmun *et al.*[11] However, an alternate technique is needed to measure the conductance in the contact-limited regime.

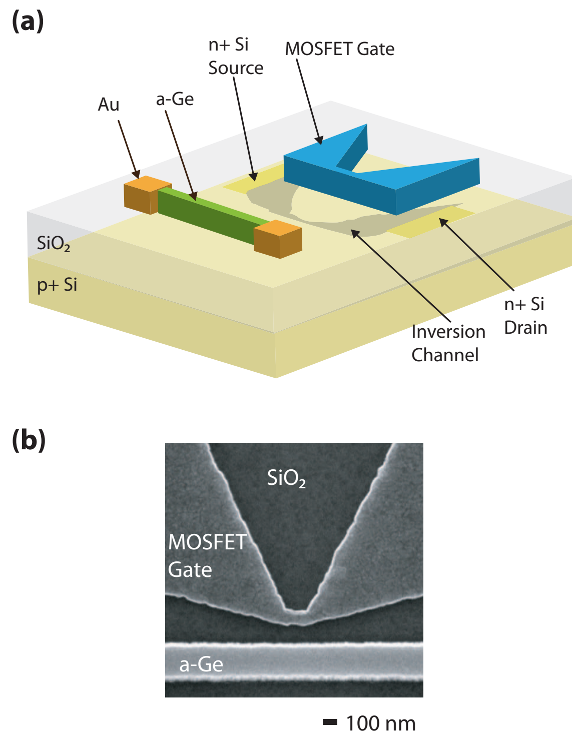

Figure 1: (a) The device consists of an n-channel silicon MOSFET posititioned approximately 100 nm away from a thin film of amorphous germanium. The gate of the MOSFET tapers to a width of ≈60 nm wide at its narrowest point and induces an inversion channel of a comparable width in the p^+ silicon substrate. Highly resistive contacts form at the interface between the amorphous germanium film and gold electrodes. The channel, or inversion region, of the MOSFET is capacitively coupled to the amorphous germanium film. (b) An electron micrograph of the gate of the n-channel silicon MOSFET and the film of amorphous germanium.

Before using the MOSFET to measure the conductance of the amorphous germanium, we characterize the MOSFET and demonstrate its sensitivity to nearby electrostatic fluctuations. We measure the conductance versus gate voltage of the MOSFET at 4 K as displayed in Figure 2(b). The gate voltage is swept from 3.6 to 7.2 V and then back down to 3.6 V, and the oscillations that we observe in the conductance are nearly identical in both directions. This is typical of a one-dimensional inversion layer where random fluctuations in the local potential at the Si/SiO_2interface cause oscillations in the conductance.[12] The gate voltage is then set to 8 V so that the channel is in inversion, and the dc current in the MOSFET is measured versus time [Figure 2(c)] at a temperature of 11 K. The prominent switching, or random telegraph noise, in the conductance is a result of a single electron being captured and emitted from a trap state in the silicon dioxide nearby the narrow constriction in the MOSFET channel.[13] The conductance of the MOSFET decreases when an electron is trapped nearby, and then increases when the electron is released, demonstrating that the MOSFET can sense the fluctuation of a single electron nearby.

The sensitivity of the MOSFET to the electrostatic environment enables it to sense charge diffusion in the nearby amorphous germanium film even when the contacts are blocking. The charge sensing measurement entails stepping the voltage on the amorphous germanium film so that charge flows in the film, and simultaneously measuring the conductance of the MOSFET as a function of time [Figure 3]. In the following measurements, we maintain a positive voltage on the gate of the MOSFET, $V_g > 6V$, to ensure that the channel is in inversion. To measure the conductance of the MOSFET, we apply an ac source-drain voltage of $V_{ds} = 5mV$ and measure the current in the MOSFET. At time t = 0, we step the voltage on the amorphous germanium V_{aGe} from -0.5 to -1 V. Even though $|V_{aGe}| < 5V$ and the contact resistance limits the current, capacitive coupling between the gold electrodes and the amorphous germanium film causes positive charge in the amorphous germanium film to flow toward the negatively biased gold electrode. The *n*-channel MOSFET senses the decrease in positive charge in the vicinity of the narrow constriction, and the conductance of the MOSFET decreases with time [Figure 3(b) and Figure 3(c). After stepping V_{aGe} back to -0.5 V, positive charge flows away from the electrode and the conductance of the

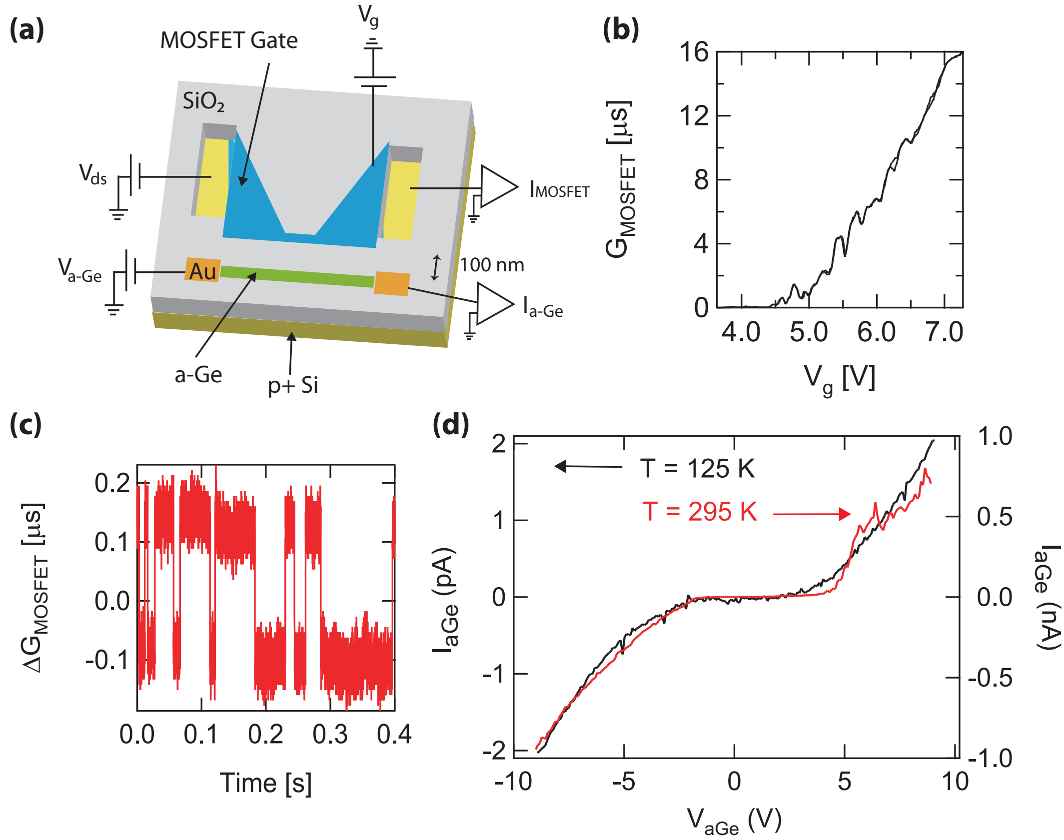

Figure 2: (a) Top view of the device structure with electrical circuits used to characterize the nanoscale MOSFET and the amorphous germanium film. (b) Conductance of the MOSFET versus gate voltage at 4 K. Oscillations in the conductance are caused by random fluctuations in the local electric potential at the Si/SiO_2 interface, and is indicative of a one-dimensional inversion channel. (c) Conductance of the MOSFET versus time with $V_{ds} = 1mV$ at a temperature of 11 K. The random telegraph noise arises because the conductance of the MOSFET is sensitive to single electron fluctuations in a nearby trap state in the silicon dioxide. The sensitivity of the MOSFET conductance to variation in the local electric potential demonstrates its capabilities as a charge sensor. (d) Current versus voltage V_{aGe} applied to the film of amorphous germanium at a temperature of 125 K (black) and 295 K (red). The non-Ohmic nature of the IV characteristic is indicative of resistive contacts. The current is immeasurable for $|V_{aGe}| \leq 5V$. The contacts become Ohmic for $|V_{aGe}| > 5V$.

MOSFET increases with time. The response of the MOSFET to the charge flow in the amorphous germanium is henceforth referred to as a charge transient.

The charge transient is analyzed as follows.[14,15] We treat the amorphous germanium as a distributed RC network, as shown in Figure 3(a). When the amorphous germanium is subject to a step voltage at one edge, charge diffuses through the film with a diffusion constant of $D = 1/R_{sq}C$ where R_{sq} is the resistance per square and C is the capacitance per unit area of the film. By solving the diffusion equation for this system, it is found that the charge per unit area at any point in the film varies with time according to $\sigma(t) \approx \sigma_0 + Aexp(-\Gamma t)$ where $\Gamma = \pi^2 D/L^2$, L is the length of the film, and D is the diffusion constant. As long as the voltage step on the amorphous germanium is sufficiently small, the conductance of the MOSFET varies linearly with the charge in the amorphous germanium film, and so $G_{MOSFET}(t) \approx G_0 + Cexp(-\Gamma t)$ where $\Gamma = \pi^2/R_{sq}CL^2$. The conductance of the amorphous germanium film is given by $G_{aGe} = w/R_{sq}L$ where w and L are the width and length of the film respectively. From this, we see that the conductance of the amorphous germanium film can be derived from the charge transient of the MOSFET. In Figure 3(b) and Figure 3(c), we fit the charge transients to this form, and extract Γ, the rate of charge flow in the film, and hence G_{aGe}. We find $G_{aGe} = 1.3 \times 10^{-17}$ S at 44 K. As we increase the temperature to 54 K, the rate Γ increases and the conductance increases to $G_{aGe} = 9.4 \times 10^{-17}$ S.

With this method, we measure the conductance of the amorphous germanium film as a function of temperature in a regime where the contacts limit the dc current (Figure 4(a), open blue squares). At each temperature in the range of 30-125 K, we step the voltage on the amorphous germanium V_{aGe} from -0.5 to -1 V, and derive the conductance G_{aGe} from the charge transient of the MOSFET. As expected, the direct current I_{aGe} is immeasurable (<10 fA) for $V_{aGe} = -1V$ throughout the temperature range of 30-295 K because this is the contact-limited regime. An additional feature of this measurement technique is that we can measure conductances smaller than 10^{-19} S with the application of only -1 V, which would be impossible with conventional current measurements.

We repeat this set of conductance measurements as a function of temperature in a regime where the contacts are Ohmic, namely $V_{aGe} \geq 5V$. We step V_{aGe} from -4.5 to -5.5 V, and derive the con-

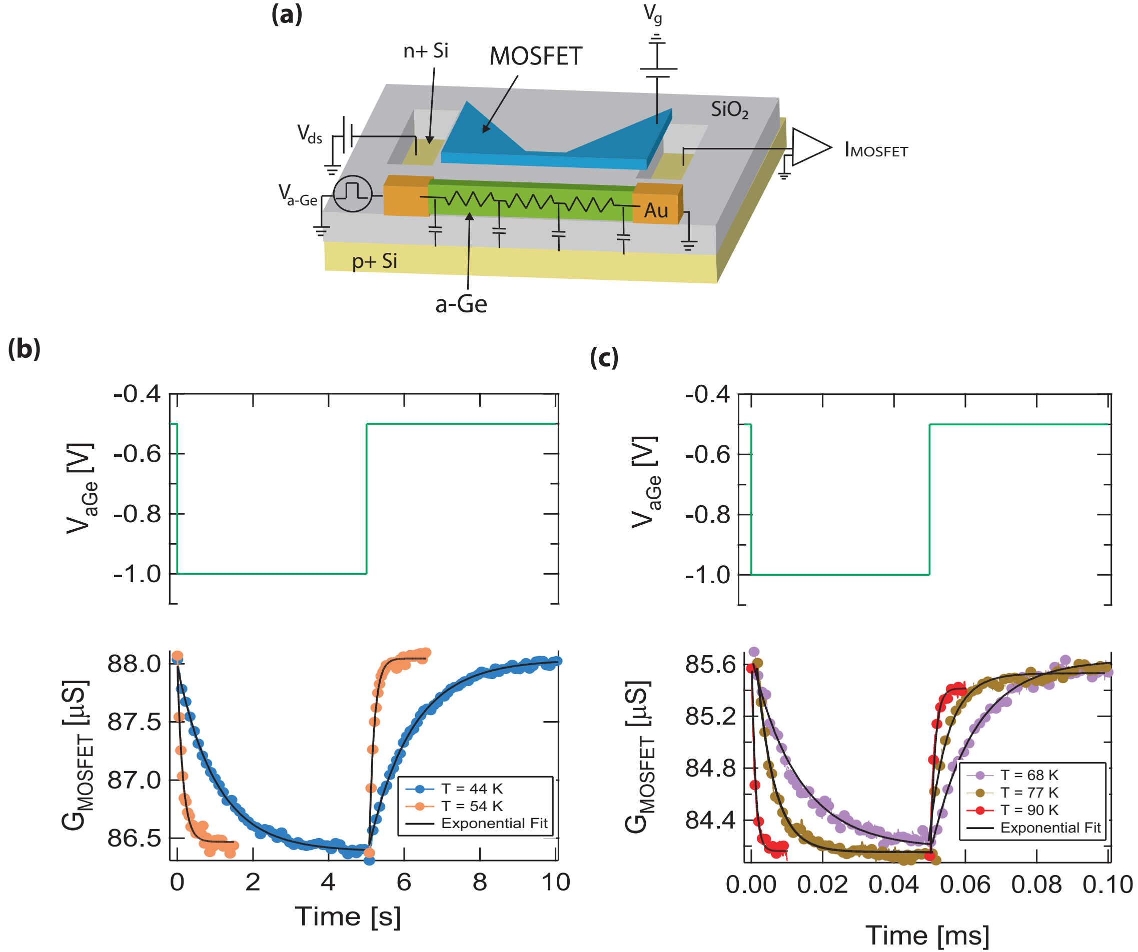

Figure 3: (a) The device and circuit used for the contact-independent conductance measurement. The amorphous germanium film is modeled as a distribued RC network. (b,c *upper panel*) The voltage on the gold electrodes adjacent to the amorphous germanium film is stepped from V_{aGe} = -0.5 V to -1 V at time t = 0. Even though the contacts are blocking, capacitive coupling between the gold electrodes and the amorphous germanium causes positive charge in the film to diffuse toward the negatively biased contacts. At a later time, V_{aGe} is stepped back to -0.5 V. (b,c *lower panel*) Conductance of the MOSFET versus time in response to charge diffusion in the film after stepping V_{aGe}. As charge diffuses in the distributed RC network of the amorphous germanium film, the conductance of the MOSFET varies exponentially with time. The solid lines are fits to $G = G_0 exp(-\Gamma t)$ where $\Gamma = \pi^2/R_{sq}CL^2$ and R_{sq} is the resistance per square of the amorphous germanium film.

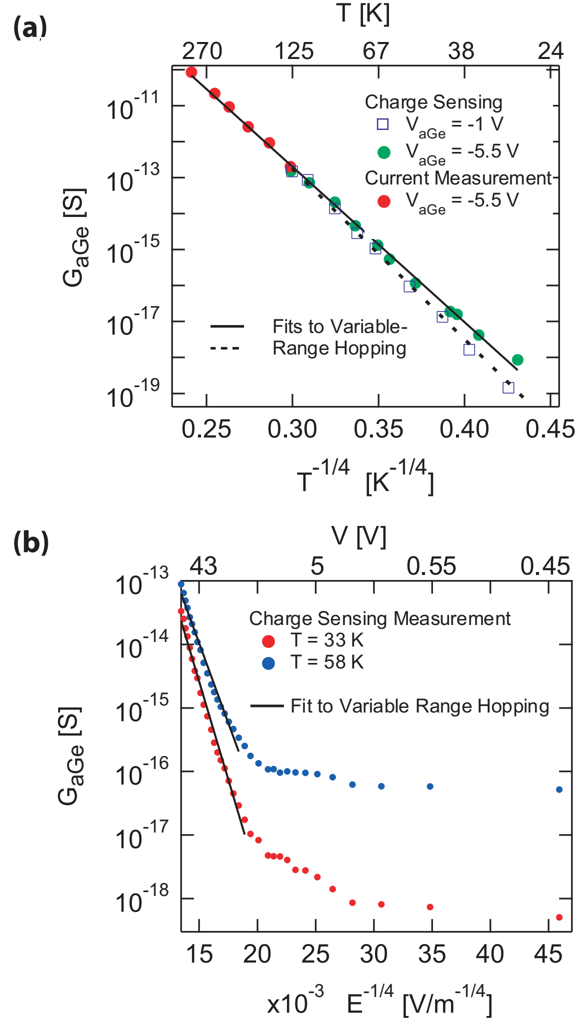

Figure 4: (a) Conductance of the amorphous germanium film versus temperature derived from sensing charge diffusion after stepping the voltage to $V_{aGe} = -1V$, where the contacts limit the resistance (blue squares), and to $V_{aGe} = -5.5V$, where the contacts are Ohmic (green circles). At temperatures $\geq$125 K, the conductance G_{aGe} is derived from measuring current I_{aGe} in the film at $V_{aGe} = -5.5V$ (red circles). As expected, current is immeasurable in the contact-limited regime, $V_{aGe} = -1V$. The lines are fits to variable-range hopping $G = G_0 exp(-T^*/T)^{1/4}$ at $V_{aGe} = -1V$ (dashed line) and at $V_{aGe} = -5.5V$ (solid line). (b) Conductance of the amorphous germanium (derived from charge sensing measurements) versus electric field applied to the amorphous germanium at a temperature of 33 K (red) and 58 K (blue). The lines are fits to variable-range hopping in a strong electric field $G = G_0 exp(-E^*/E)^{1/4}$.

ductance G_{aGe} from the charge transient at each temperature in the range of 18-125 K (Figure 4(a), green circles). At temperatures ≥125 K and $V_{aGe} = -5.5V$, we obtain the conductance of the amorphous germanium G_{aGe} using conventional measurements of current I_{aGe} (red circles). At 125 K, we measure the conductance using both methods, and find that the two agree within a factor of 1.3, thereby validating our method for obtaining the conductance from the charge transient.

In amorphous germanium, charge transport is dominated by hopping between localized states distributed in energy about the Fermi energy.[16] At high temperatures, hopping is expected to occur between nearest neighbor sites with an activation energy given by the distribution in nearest-neighbor site energies. Mott argued that as the temperature decreases, electrons do not typically hop between nearest neighbor sites, but rather to sites that are further away but are closer in energy, via phonon-assited tunneling.[17] This model is known as variable-range hopping, and the conductance is given by[17] $G = G_0 exp(-T^*/T)^{1/4}$. We fit the conductance versus temperature at $V_{aGe} = -5.5V$ to this model (Figure 4(a), solid line), and find $T^* = 9.8 \times 10^7$ K, which is in agreement with previous measurements of amorphous germanium.[18]

Knowing that the transport in the Ohmic regime is described by variable-range hopping, we fit the conductance versus temperature in the contact-limited regime ($V_{aGe} = -1V$) to this model (Figure 4(a), dashed line). When we extrapolate the fit to temperatures greater than 125 K, we find the conductance should be $G_{aGe} \geq 10^{13}$ S. With $V_{aGe} = -1V$, the current in the amorphous germanium at these high temperatures should be easily measurable (>100 fA) and the fact that it is not is consistent with our conclusion that the contacts limit the dc current.

We use the charge sensing method to measure the field dependence of the conductance $G_{aGe}(E)$ at temperatures of 33 and 58 K as shown in Figure 4(b). We perform this measurement by applying a static field across the amorphous germanium: one gold electrode in held at ground while the other is held at a negative voltage. Then we rapidly step the voltage on the latter electrode by an additional -0.5 V and obtain the conductance from the charge transient. For example, to measure the conductance G_{aGe} at an applied bias voltage of $V_{aGe} = -10V$, we apply a fixed voltage $V_{aGe} = -9.5V$, rapidly step the voltage to $V_{aGe} = -10V$ and measure the resulting charge transient

in the MOSFET. In the model of variable-range hopping, when the electric field is sufficiently strong, all successive electronic sites along the field will be lower in energy than the previous sites. Therefore, phonons are emitted as charges hop along the field, and the conductance is temperature independent. In this regime, the conductance is expected to follow[19] $G = G_0 exp(-E^*/E)^{1/4}$. The high-field regime of the conductance $G_{aGe}(E)$ is fit to this model (Figure 4(b), black lines), and we extract a value for E^* of 7.7×10^{12} V/m from the fit.

We take the values of E^* and T^* from the fits to variable-range hopping (Figure 4), and use the expressions[19,20] $T^* = 16/k_B D(E_F)a$ and $E^* \approx 16/eD(E_F)a^4$ to find a density of states at the Fermi energy $D(E_F) = 1.6 \times 10^{18}$ eV^{-1} cm^{-3} and a localization length $a \approx 1$ nm. These values are consistent with those previously reported in amorphous germanium: $D(E_F) = 1.5 \times 10^{18}$ eV^{-1} cm^{-3} and $a = 1$ nm.[18] The transition to variable-range hopping in a strong electric field, as shown in Figure 4(b), is expected to occur when the decrease in potential energy $eER(T)$ over a typical hopping distance $R(T)$ becomes comparable to the energy band within which an electron can hop $\Delta\varepsilon(T)$ so that phonons are emitted as the electron hops along the field.[19] The critical field E_C for a transition into this regime is given by $eE_C R(T) \approx \Delta\varepsilon(T)$, or $E_C \approx k_B T/ea$. From the curve in Figure 4(b), we find the onset of the strong-field regime at $T = 58$ K at a critical field of $E_C \approx 6.1 \times 10^6$ V/m from which we find $a \approx 0.8$ nm, comparable to ≈ 1 nm found above. By successfully extracting the density of states and localizaiton length from our measurements, we demonstrate that this charge sensing technique accurately characterizes a thin film.

We expect our device structure to enable a contact-independent measurement of field-effect mobility. By modulating the voltage difference between the thin film and the underlying silicon substrate, the substrate can serve as a back gate and one can measure the conductance of the film as a function of gate voltage.[14] In a film of amorphous germanium, the density of states about the Fermi energy is approximately constant and so we do not observe a change in conductance with gate voltage.

In summary, we have demonstrated a method of electrically characterizing a thin film that is insensitive to contact effects and can measure conductance as low as 10^{-19} S with application of

only 1 V to the film. The technique is applicable to any thin solid film for which the contacts interfere with current measurements or where the current is immeasurable because the film is highly resistive. This method can be used if an insulating layer is placed between the contacts and the film to protect the film from the contact material, or for measuring field-effect mobility. By comparing the contact-independent charge sensing measurement with a contact-dependent current measurement, one can discern whether the contacts influence the current measurement, and thereby chose a non-invasive contact material. This meaurement method offers the potential to advance progress in developing new materials such as novel organic semiconductors or nanoscale materials where contact effects often stymie efforts to electrically characterize and to understand the material properties. The ability to identify a non-invasive contact material could accelerate the application of new materials in devices.

Acknowledgement

We are grateful to N. Ray and the staff at the MIT Microsystems Technology Laboratories for experimental help. This work was supported by the U.S. Army Research Office under contract W911 NF-07-D-0004 and by the Department of Energy under award number DE-FG02-08ER46515.

Supporting Information Available

Details on device fabrication, instrumentation, and the mathematical derivation of the conductance measurement. This material is available free of charge via the Internet at `http://pubs.acs.org`.

References

(1) Zaumseil, J.; Baldwin, K. W.; Rogers, J. A. *J. Appl. Phys.* **2003**, *93*, 6117.

(2) Xia, F.; Perebeinos, V.; ming Lin, Y.; Wu, Y.; Avouris, P. *Nature Nanotechnology* **2011**, *6*, 179.

(3) Petrović, A.; Pavlica, E.; Bratina, G. In *Interface Controlled Organic Thin Films*; et al., H.-G. R., Ed.; Springer-Verlag, 2009; pp 205–210.

(4) Shpaisman, H.; Har-Lavan, R.; Stein, N.; Yaffe, O.; Korobko, R.; Seitz, O.; Vilan, A.; Cahen, D. *Advanced Functional Materials* **2010**, *20*, 2181–2188.

(5) Stein, N.; Korobko, R.; Yaffe, O.; Lavan, R. H.; Shpaisman, H.; Tirosh, E.; Vilan, A.; Cahen, D. *J. Phys. Chem. C* **2010**, *114*, 12769–12776.

(6) Liu, Z.; Kobayashi, M.; Paul, B. C.; Bao, Z.; Nishi, Y. *Phys. Rev. B* **2010**, *82*, 035311.

(7) von Wrochem, F.; Gao, D.; Scholz, F.; Nothofer, H.-G.; Nelles, G.; Wessels, J. M. *Nature Nanotechnology* **2010**, *5*, 618.

(8) Gundlach, D.; Zhou, L.; Nichols, J. A.; Jackson, T. N.; Necliudov, P.; Shur, M. *J. Appl. Phys.* **2006**, *100*, 024509.

(9) Salomon, A.; Cahen, D.; Lindsay, S.; Tomfohr, J.; Engelkes, V. B.; Frisbie, C. D. *Adv. Mater.* **2003**, *15*, 1881.

(10) Bau, Z.; Locklin, J. *Organic Field-Effect Transistors*; CRC Press, Taylor and Francis Group, 2007.

(11) Osmun, J. W.; Fritzsche, H. *Appl. Phys. Lett.* **1970**, *16*, 87–89.

(12) Licini, J. C.; Bishop, D. J.; Kastner, M. A.; Melngailis, L. *Phys. Rev. Lett.* **1985**, *55*, 2987.

(13) Ralls, K. S.; Skocpol, W. J.; Jackel, L. D.; Howard, R. E.; Fetter, L. A.; Epworth, R. W.; Tennant, D. M. *Phys. Rev. Lett.* **1984**, *52*, 228.

(14) MacLean, K.; Mentzel, T. S.; Kastner, M. A. *Nano. Lett.* **2011**, *11*, 30–34.

(15) Senturia, S.; Sechen, C.; Wishneusky, J. *Appl. Phys. Lett.* **1977**, *30*, 106.

(16) Miller, A.; Abrahams, S. *Phys. Rev.* **1960**, *120*, 745.

(17) Mott, N. F. *J. Non-cryst. Solids* **1968**, *1*, 1.

(18) Knotek, M. L.; Pollak, M.; Donovan, T. M.; Kurtzman, H. *Phys. Rev. Lett.* **1973**, *30*, 853–856.

(19) Shklovskii, B. I. *Soviet Physics- Semiconductors* **1973**, *6*, 1964–1967.

(20) Bottger, H.; Bryksin, V. V. *Hopping Conduction in Solids*; Akademie-Verlag, 1985.

Graphical TOC Entry