### Citation

### As Published
http://dx.doi.org/10.1109/IEDM.2010.5703423

### Publisher
Institute of Electrical and Electronics Engineers (IEEE)

### Version
Final published version

### Accessed
Sun Apr 24 10:43:19 EDT 2016

### Citable Link
http://hdl.handle.net/1721.1/72955

### 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.
Gigahertz Ambipolar Frequency Multiplier based on CVD Graphene
Han Wang, Allen Hsu, Ki Kang Kim, Jing Kong, and Tomás Palacios
Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge MA 02139, USA. Tel: +1 (617) 460-7364, Fax: +1 (617) 258-7393, Email: hanw@mit.edu

Abstract
Ambipolar transport in graphene offers great opportunities for novel device and circuit applications. This paper discusses the RF performance of CVD grown graphene transistors for the first time. Then, a new graphene ambipolar frequency multiplier that can operate at 1.4 GHz with extremely high output spectral purity (> 90%) is demonstrated. These GHz graphene frequency multipliers, made from wafer-scale graphene synthesis and fabrication processes, demonstrate the great potential of graphene-based ambipolar devices for RF and mixed-signal applications.

Introduction
The unique ambipolar transport properties of graphene, combined with its high mobility (>100,000 cm²/Vs in suspended graphene, and >10,000 cm²/Vs in graphene on a substrate at room temperature) [1, 2], enable the development of a new form of non-linear electronics for radio frequency (RF) and mixed-signal applications [3, 4, 5]. This paper presents a new graphene ambipolar frequency multiplier that can operate at gigahertz frequencies. The contributions of this paper are three-fold. First, RF performance of graphene field effect transistors (GFET) grown by chemical vapor deposition (CVD) is presented for the first time. Second, this device demonstrates ambipolar frequency multiplication at 1.4 GHz. This improves frequency performance of graphene frequency multipliers by more than 4 orders of magnitude from previous work [3, 4, 6], making it suitable for a much wider range of applications in communication systems. Finally, these devices show a very high spectral purity at the output without any filtering, where more than 90% of the RF power is at the useful frequency. This excellent spectral purity is highly desirable for high frequency mixed-signal circuits.

CVD Growth and Device Fabrication
Single-layer graphene films were grown by CVD on copper substrates [7]. Firstly, copper foils are annealed at 1000°C in H₂ (350 mTorr for 30 minutes) to increase the grain size of copper. Then, they are exposed to CH₄ under low-pressure condition (1.6 Torr) to initiate graphene growth. After the growth, polymethyl methacrylate (PMMA) is coated on the graphene film and the copper substrate is etched away in copper etchant and diluted HCl. Films are then transferred onto polished Si wafers with a 300 nm thermally-grown SiO₂ on top (Fig. 1). As shown in Fig. 1, Raman spectroscopy confirms that single-layer graphene with uniformity greater than 95% is obtained. (c) AFM image of the graphene obtained with a Veeco Dimension 3100 system showing excellent uniformity. (d) Raman spectrum confirms the presence of single-layer graphene.
Ni/ 200 nm Au/ 50 nm Ni metal stack (Fig. 2). DC and RF characterization of the devices was performed using an Agilent 4155C Parameter Analyzer and an Agilent N5230 Vector Network Analyzer respectively. The devices were measured at room temperature under vacuum (1.4x10^{-4} Torr) to reduce hysteresis.

**DC and RF characteristics**

Fig. 3 shows the DC characteristics of the fabricated GFETs. The minimum conduction point is at 3.7 V. The peak transconductance for hole and electron conduction is -68 mS/mm and 40 mS/mm respectively. Fig. 4 shows the RF characteristics of the GFETs. The extrinsic current-gain cut-off frequency, \( f_T \), and the extrinsic maximum oscillation frequency, \( f_{\text{max}} \), for hole conduction are \( f_{T, \text{Hole}} = 2.6 \text{ GHz} \) and \( f_{\text{max, Hole}} = 3.8 \text{ GHz} \) and for electron conduction are \( f_{T, \text{Electron}} = 2.1 \text{ GHz} \) and \( f_{\text{max, Electron}} = 3.0 \text{ GHz} \). Both hole and electron transports are important for frequency doubling since, as it is described in the next section, the conduction in these devices happens by alternating half cycles of holes and electrons. The frequency performance will be limited by the lower of the two conduction modes.

**Frequency Doubling at Gigahertz Frequencies**

Fig. 5 shows the test circuit for frequency doubling. Low loss bias tees are used both at the input and the output to combine DC and RF signals, and provide isolation between them. Tuners are used at the input to provide adequate impedance matching. Under the test conditions, the gate of the GFET is biased at its minimum conduction point. As a sinusoidal RF signal is superimposed to the gate DC bias, the GFET will operate in alternating half cycles of electron and hole conduction due to the V-shape transfer characteristics of the GFET. The sinusoidal input signal is, hence, full-wave rectified by the GFET, giving an output signal that has a fundamental frequency twice of the input frequency.

Fig. 6 shows the measurement setup. Clear frequency multiplication is observed between the input signal and the output signal, both measured by an Agilent DSA90604A oscilloscope. Fig. 7 plots both the input signal at 700 MHz and the output signal, which has a fundamental frequency of 1.4 GHz. Frequency doubling is clearly demonstrated. This frequency doubler device shows high spectral purity in the output RF signal, where more than 90% of the output RF energy is at the useful frequency (1.4 GHz). Frequency doubling at 1.4 GHz is also confirmed by the output signal spectrum measured by an Agilent N9010A spectrum analyzer.

In the output signal, the signal power at \( f_{\text{out}} = 2f_{\text{in}} = 1.4 \text{ GHz} \) is
about 10 dB higher than the signal power at $f_{\text{out}} = f_{\text{in}} = 700$ MHz (Fig. 8). This is the first time frequency doubling has been achieved with a single transistor at gigahertz frequencies without any filtering elements.

**Conversion Gain**

Fig. 9 shows the output power at $f_{\text{out}} = 2f_{\text{in}}$, $P_{\text{out},2f_{\text{in}}}$ (blue square), against input power at $f_{\text{in}}$, $P_{\text{in},f_{\text{in}}}$. The output power increases with the input power at a slope of 20 dB/dec. This agrees with the fact that the signal at $f_{\text{out}} = 2f_{\text{in}}$ is generated by the quadratic component in the transfer characteristics of the GFET and its power increases with a slope of 2 with respect to input power when plotted in logarithmic scale. The conversion gain (red dot), defined as: $\text{gain} = P_{\text{out},2f_{\text{in}}} / P_{\text{in},f_{\text{in}}}$ increases with input power up to $P_{\text{in},f_{\text{in}}} = 2$ dBm.

The -3dB cut-off frequency is 1.5 GHz, at about 70% of $f_{T,\text{Electron}} = 2.1$ GHz. Owing to the high carrier mobility and high saturation velocity, the bandwidth is not limited by the carrier transit time, but mainly by the RC constant of the device.

**-3dB Cut-off Frequency**

The frequency dependence of the gain is characterized and shown in Fig. 10. The -3dB cut-off point is 1.5 GHz. Bandwidth is not limited by the carrier transit time, but mainly by the RC constant of the device.
the carrier transit time, but mainly by the RC time constant of the device.

**Effects of Asymmetry in Device Characteristics**

By simulating the input and output signals from GFETs using MATLAB, we study the effects of asymmetry in GFET transfer characteristics on the spectral purity at the output. As shown in Fig. 11(a), devices with transfer characteristics ranging from perfect symmetry to unipolar are simulated. The hole conduction branch of these devices’ transfer characteristics is assumed to be identical to the device in Fig. 3. The device is assumed to be biased at the minimum conduction point. Fig. 11(b) shows the simulated relative output power at $f_{\text{out}}=f_{\text{in}}$ and $f_{\text{out}}=2f_{\text{in}}$. As the device transfer characteristics changes from perfect symmetry to unipolar, the relative power at $f_{\text{out}}=f_{\text{in}}$ increases from 0 dB to 13.5 dB while the power at $f_{\text{out}}=2f_{\text{in}}$ decreases from 14 dB to 11 dB. This result shows that, for a given input power, as the device transfer characteristics becomes more asymmetric, the quadratic term in the transfer characteristics decreases while the linear term increases, leading to a reduction in the output power at $f_{\text{out}}=2f_{\text{in}}$ (and other even order harmonics) and an increase in the output power at $f_{\text{out}}=f_{\text{in}}$ (and other odd order harmonics). Hence, the output spectral purity for frequency doubling decreases as a result. As shown in Fig. 11(b), perfectly symmetric GFETs can achieve a spectral purity that is well above 90% (vs. 35% for unipolar device similar to conventional FET). This highlights the great advantage of ambipolar frequency multipliers in terms of output spectral purity as compared to the conventional frequency multipliers based on unipolar devices.

**Conclusion**

In conclusion, this paper presents a new ambipolar frequency multiplier based on CVD graphene with operation up to 1.4 GHz. These new ambipolar frequency multipliers can achieve extremely high spectral purity in the output signal (> 90%), which is confirmed by both experimental results and numerical simulations. With the graphene used in the devices grown by wafer-scale CVD synthesis and the device fabrication processes compatible with traditional technologies in semiconductor industry, these gigahertz graphene frequency multipliers demonstrate the great potential of graphene-based ambipolar devices for RF and mixed-signal applications, and possible integration with Si electronics in the near future.

**Acknowledgements**

This work has been partially supported by the ONR GATE MURI program (Dr. Chagaan Baatar) and by the MSD Focus Center.

**References**