Flexible Graphene Field-Effect Transistors for Microwave Electronics

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Abstract — The high-frequency characteristics of graphene field-effect transistors (GFETs) has received significant interest due to the very high carrier velocities in graphene. In addition to excellent electronic performance, graphene possesses exceptional mechanical properties such as high flexibility and strength. Here, we demonstrate the potential of flexible-GFETs and show that the combination of electrical and mechanical advantages of graphene result in gigahertz-frequency operation at strain values up to 2%. These devices represent the only reported technology to achieve gigahertz-frequency power gain at strain levels above 0.5%.

Index Terms — graphene, high-frequency, flexible electronics.

I. INTRODUCTION

The growing demand for pliable electronics for applications such as e-paper, flexible displays, and wearable communication technologies has in turn motivated the development of flexible field-effect transistors (FETs). Many materials have been suggested as the channel material for flexible FET applications, including organic thin films [1], silicon nanomembranes [2], III-V metal-oxide-semiconductor thin-films [3], and carbon nanotubes [4]. However, all have been either limited in the mechanical flexibility or electronic performance, and to date, no flexible technology has achieved both unity-current-gain frequencies, $f_T$, and unity-power-gain frequencies, $f_{\text{max}}$, in the GHz regime at strains above 0.5%. The lack of a scalable technology, which can yield devices demonstrating high values of $f_{\text{max}}$ at high strain, provides a clear motivation for the development of a technology that can satisfy both requirements.

Graphene, a two-dimensional semiconducting sheet of carbon, has electronic and mechanical properties that make it advantageous for the fabrication of FETs that require both high flexibility and high operating frequencies. In terms of electrical properties, the high carrier mobility and saturation velocity make graphene a promising candidate for high-frequency analog/RF applications [5]. In fact, graphene FETs (GFETs) on rigid substrates have demonstrated values of $f_{\text{max}}$ of up to 34 GHz at only 600-nm channel length [6].

Recently, there have been preliminary demonstrations the flexible GFETs; however, the device high-frequency performance was mainly limited to sub-gigahertz regime due to the use of relatively low-quality graphene [7]. Here, we use chemical vapor deposition (CVD) to produce large-area films of graphene, demonstrating electronic properties comparable to those of exfoliated graphene [8]. CVD graphene retains superb mechanical properties, with flexible devices fabricated from CVD graphene demonstrating stable DC electronic properties [9]. In this work we demonstrate that FETs can be fabricated from CVD graphene with $f_{\text{max}}$ values of 3.7 GHz and withstand strains up to 1.75%, corresponding to a bend radius as small as 3.6 mm.

II. DEVICE FABRICATION

GFETs were fabricated on 127-μm-thick polyethylene naphthalate (PEN) substrates (DuPont Teijin Films) with a RF-probable split-gate geometry as shown in Fig. 1. The fabrication starts with electron-beam-lithography(EBL)-defined two-fingered local bottom-gates followed by

Fig. 1. (a) Schematic of GFET fabricated on PEN, a flexible substrate. (b) SEM image of GFET fabricated with a channel length of 500 nm.
evaporation of 1 nm of Ti followed by 30 nm Au-Pd alloy and associated lift-off. A 6-nm gate dielectric of HfO$_2$ ($\kappa \approx 13$) is conformably grown by atomic layer deposition (ALD) at 150 °C. Single-crystals of graphene are grown by chemical vapor deposition (CVD) and then mechanically transferred onto the gate. Devices are then etched into the desired shape using standard EBL followed by an O$_2$-plasma etch. The devices are completed by evaporating Ti/Pd/Au (1nm/15nm/50nm) source and drain electrodes to contact the graphene. Devices measured here have gate lengths of 500 nm, source-to-drain spacing of 900 nm, and channel width of 30 μm. Figure 1b shows an SEM micrograph of a completed GFET device fabricated on a PEN substrate.

III. MEASUREMENTS AND RESULTS

Flexible GFET DC performance is shown in Figs. 2a-c, where channel current, $I_{ch}$, is displayed against source-to-drain voltage, $V_{sd}$, with gate-to-source voltage, $V_{gs}$, varying from 0.25 V to -1 V in 0.25 V steps. All device characteristics are measured under ambient conditions. Uniaxial tensile strain is applied along the axis of the channel width under two-point bending conditions. The strain is calculated from the bending geometry assuming frictionless end supports. The same DC measurement is shown at three different strain values of 0%, 1.25%, and 1.75% in Fig. 2a-c.

At 0% strain, measured values of transconductance, $g_m$, and output resistance, $r_o$, are 5.1 mS and 259 Ω, respectively, at a bias point of $V_{gs} = -0.25$ V and $V_{sd} = 0.5$ V. We note that thermal operating limits of the polymer substrate prevent output characteristics from being measured above $V_{sd} = 0.5$ V, beyond which it was found that Joule heating in the channel begins to irreversibly deform the PEN substrate. This limits devices from being operated in a fully saturating regime, thus limiting the maximum achievable values of $g_m$ and $r_o$ in our devices fabricated on this substrates.

The transconductance and output resistance remain relatively constant up to 1.1% strain (Fig. 4b). Changes in $I_d$ with increasing strain, as seen in Fig. 2a-c, are correlated to the observed shifts in the charge neutrality point in the linear transport region (not shown). While the exact cause of this shift is unknown, it could be explained by change in the gate capacitance of the devices as shown in Fig. 4c.

Fig. 3 shows RF characteristics for this same GFET device measured at 0% and 1.25% strain. Both current-gain ($h_{21}$) and unilateral power gain ($U$) are extracted from S-parameters measured at $V_{sd} = 0.5$ V. $V_{gs}$ values are chosen to maximize device transconductance and change with strain due to the charge neutrality point shifts observed. The device demonstrates extrinsic cut-off frequency values (without any de-embedding) of $f_t = 7.2$ GHz and $f_{max} = 2.6$ GHz at 0%
strain, as shown in Fig. 3a. At 1.25% strain, \( f_1 \) is 10.7 GHz and \( f_{\text{max}} \) up to 10.7 GHz are observed (Fig. 3b). The RF performance does not degrade from its unstrained value up to strain of 1.75%. Above this strain value, most devices begin to fail due to cracking of the gate electrode, accompanied by irreversible degradations in electronic characteristics. The highest strain we could achieve before the devices fail permanently was 2% corresponding to a bend radius of 3.2 mm.

IV. DISCUSSION

We further analyze the evolution of relevant device parameters with strain in Fig. 4. Low-bias field-effect mobility, \( \mu \), calculated from \( \mu = (L/W) \left( g_m/C_d \right) \), where \( L \) is the channel length, \( W \) is the channel width, \( C_d \) is the gate capacitance per unit area (extracted from the S-parameter measurements) is shown in Fig. 4a. Mobility remains uniform with device flexure, exhibiting less than \( \pm 30\% \) variance across the entire measured strain range up to 2% strain, in good agreement with previous experimental observations [10], and demonstrating the stability of the intrinsic electronic properties of the CVD graphene channel. \( g_m \) (Fig. 4b) exhibits low variance (less than \( \pm 25\% \)) up to strains of \( \epsilon_{yy} = 1.1\% \). Fig. 4c plots device gate capacitance extracted directly from measured scattering parameters, \( C_g \), as a function of strain. At strains greater than 1.1%, the variation in \( C_g \) with strain is likely due the changes in the dielectric and dielectric/gate-metal integrity, which are also most likely causing the change in \( g_m \) at high strains. Fig. 4d plots cut-off frequency as a function of strain. Both \( f_1 \) and \( f_{\text{max}} \) demonstrate low variance (less than \( \pm 20\% \)) with strain up to 1.1%, above which an increase in both \( f_1 \) and \( f_{\text{max}} \) of up to 40% is observed. The cause of this increase needs further investigation. Above 1.5% strain the high-frequency performance starts to degrade, matching similar degradation in the DC characteristics.

V. CONCLUSION

In conclusion, we demonstrate flexible GFETs fabricated from CVD graphene which display extrinsic values of \( f_1 \) and \( f_{\text{max}} \) up to 10.7 GHz and 3.7 GHz, respectively, with strain limits of 2%. This is the first example of a flexible technology exhibiting both gigahertz-frequency power gain and strain limits above 0.5%. This work demonstrates the potential of CVD graphene as a material to enable a wide-range of highly flexible electronic technologies requiring analog FETs operating in the gigahertz frequency range.

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