Graphene Field-Effect Transistors with Gigahertz-Frequency Power Gain on Flexible Substrates

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Recent interest in the development of flexible electronics operating at radio-frequencies (RF) requires materials that combine excellent electronic performance with the ability to withstand high levels of strain. Materials such as silicon nanomembranes (SiNMs), III-V metal-oxide-semiconductor thin-films and nanowires, indium-gallium-zinc-oxide, AlGaN/GaN heterostructures, carbon nanotubes (CNTs), and graphene have all been proposed for use in flexible RF electronics. However, enhancements to electronic performance have been achieved at the expense of device flexibility; to date, no flexible technology has achieved both unity-current-gain frequencies, f_T, and unity-power-gain frequencies, f_{max}, in the gigahertz regime at strains above 0.5%.

Graphene's unique electronic and mechanical properties make it a promising material for the fabrication of field-effect transistors (FETs) which require both high flexibility and high operating frequencies. While graphene has no band-gap, rendering it poorly suited for digital applications, its high carrier mobility, saturation velocity, and current-carrying capacity make it a promising candidate for high-frequency analog applications.[1] Furthermore, the large-area films of graphene requisite for commercial fabrication of graphene-based technologies can be produced using low-cost, chemical vapor deposition (CVD) synthesis.[2] CVD graphene films display excellent electronic properties,[3] and FETs fabricated from CVD graphene on flexible substrates maintain stable DC characteristics to high levels of strain.[4]

We fabricate graphene FETs (GFETs) on flexible, polyethylene naphthalate (PEN) substrates utilizing CVD graphene as the device channel material, as shown in Fig. 1. Our GFETs demonstrate f_T and f_{max} up to 10.7 and 3.7 GHz, respectively, with strain limits of 1.75% (Fig. 2). As seen in Fig. 3, these devices represent the only reported technology to achieve gigahertz-frequency power gain at strain levels above 0.5%. As such, they demonstrate the potential of CVD graphene as a material to enable a broad range of flexible electronic technologies which require both high-flexibility and RF operation.

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[1] Schwierz, F. Graphene transistors. *Nat Nanotechnol* **2010,** *5* (7), 487-496.

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[4] Lee, S. K. *et al*. Stretchable Graphene Transistors with Printed Dielectrics and Gate Electrodes. *Nano Lett* **2011,** *11* (11), 4642-4646.

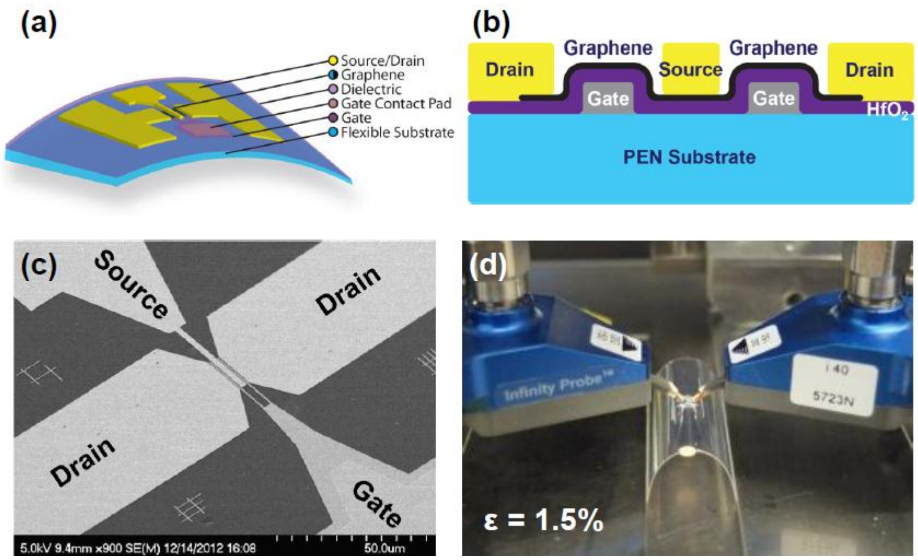


Figure 1: Flexible GFET Design: (a) Schematic of GFET fabricated on PEN, a flexible and transparent substrate. (b) Cross-sectional schematic of flexible GFET device. (c) Scanning electron migrograph of GFET fabricated with a 500 nm gate length and 900 nm source-to-drain spacing. (d) Photograph of electronic measurement approach for GFET under 1.5% strain.

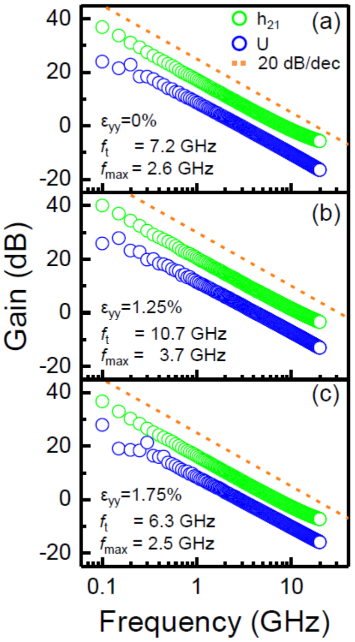
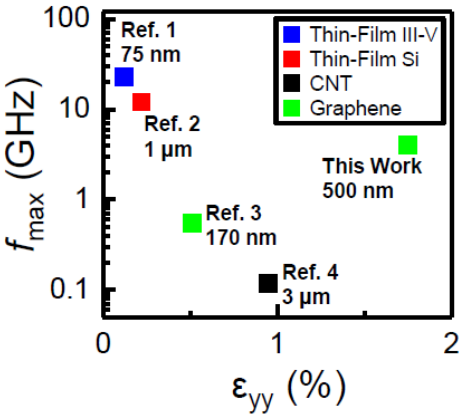


Figure 2: High-frequency device characteristics: Current gain (h_{21}) and unilateral power gain (U) plotted as a function of frequency (without de-embedding) measured at strain values of (a) 0%, (b) 1.25%, and (c) 1.75%. Values of extrinsic f_T and f_{max} are calculated for each strain state.



1. C. Wang *et al*. Nano Lett., 2012.
2. L. Sun *et al*. Small, 2010.
3. C. Sire *et al*. Nano Lett., 2012.
4. C. Wang *et al*. Nano Lett., 2012.

Figure 3: Comparison of f_{max} and strain limits of flexible FET technologies: Channel lengths of the associated devices yielding these performances are noted.