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Two-Dimensional Crystals for Ubiquitous Electronics

Han Wang, Allen Hsu, Lili Yu, Yi-Hsien Lee, Ki Kang Kim, Jing Kong, Tomas Palacios
Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge MA 02139

Two-dimensional (2D) crystals, including graphene, hexagonal boron nitride and transition metal dichalcogenides (TMD) materials, have outstanding properties for developing the next generation of electronic devices [1]. Graphene was the first 2D crystal to attract the attention of scientists and engineers. The symmetry of its honeycomb lattice structure confers on it very unique transport properties, among them a very high electron and hole mobility, which can exceed 200,000 cm^2/Vs at T=5 K and 100,000 cm^2/Vs at T=240 K [2], the highest ever reported for any semiconductor. In addition, the density of states in graphene is zero at the Dirac point and increases linearly for energies above and below it, which allows for carrier modulation. Furthermore, the carriers in 2D crystals are confined to a layer that is only one-molecular-layer thick. This allows unprecedented electrostatic confinement, and also makes 2D materials mechanically flexible and optically transparent. On the other hand, the lack of bandgap in graphene can be compensated by integrating it with other 2D materials such as MoS_2 from the TMD family [3, 4]. As a 2D crystal, MoS_2 shares many of graphene's advantages for electronic applications while its 1.8 eV bandgap makes it an ideal material for building logic circuits to complement graphene.

In this work, we demonstrate some important building blocks for future 2D-material-based IC on flexible substrates, such as plastics, paper and textiles. These basic analog building blocks include ambipolar frequency multipliers [5, 6], graphene RF mixers [7], graphene oscillators [8], and graphene phased shift keying devices [9], as well as the technology for fabricating flexible devices and circuits on plastic substrates. We also construct integrated logic circuits based on MoS_2, including an inverter, a NAND gate, a memory device and a ring oscillator. Prototypes of these building blocks are an important step towards a new generation of technologies in which electronics can be seamlessly integrated into the objects of daily life, from plastic and paper cups with integrated temperature sensors and clothing with embedded RF antennas, to smart contact lenses that communicate with our cell phones and display relevant information to the wearer.

Figure 1 shows the test circuit for graphene ambipolar frequency multipliers. Figure 1(b) plots both the input and output signals of the frequency multiplier, which are at 3 GHz and 6 GHz respectively. Frequency doubling is clearly demonstrated. Figure 1(c) shows the experimental demonstration of a graphene frequency mixer while Figure 1(d) shows the output spectrum of a graphene oscillator.

Figure 2 shows a 5-stage ring oscillator constructed to assess the high frequency switching capability of MoS_2 and for evaluating the material's ultimate compatibility with conventional circuit architecture. The ring oscillator, which integrates 12 bilayer MoS_2 FETs together, was realized by cascading five inverter stages in a close loop chain (Figure 2B). At V_{dd}=2 V, the fundamental oscillation frequency is at 1.6 MHz. The frequency performance of this ring oscillator, while operating at a much lower V_{dd}, is at least an order of magnitude better than the fastest integrated organic semiconductor ring oscillators. It also rivals the speed of ring oscillators constructed from the printed ribbons of single-crystalline silicon reported in the literature, hence demonstrating the great potential of 2D crystal materials for large area flexible electronics applications.

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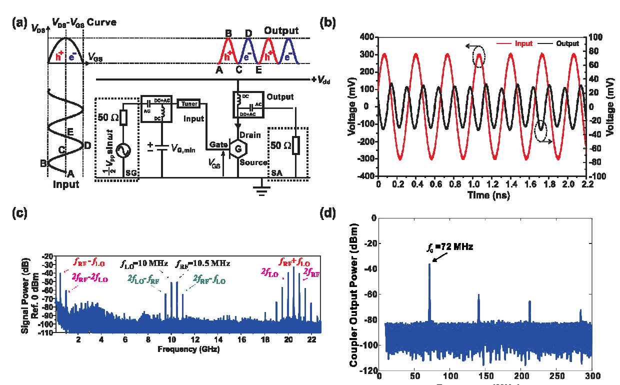

Figure 1 (a) Application circuit of graphene frequency multipliers. (b) input (red curve) and output (black curve) signals of a 6 GHz graphene frequency multiplier. (c) output signal spectrum of a graphene RF mixer. (d) output spectrum of a graphene electrical oscillator.

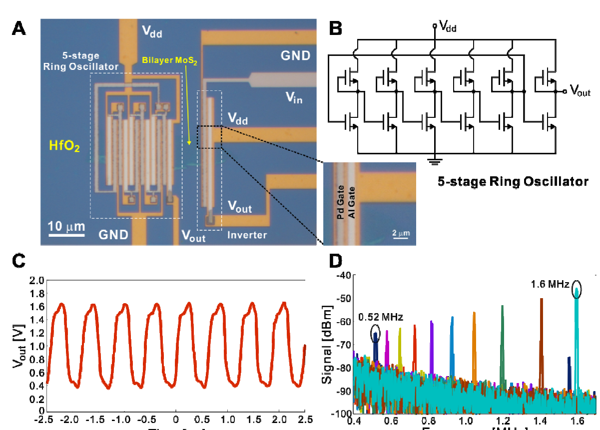

Figure 2 A 5-stage ring oscillator based on bilayer MoS_2.