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Ultrathin GaGeTe p-type transistors

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We exfoliated bulk GaGeTe crystals down to ultrathin flakes using the Scotch tape method and fabricated field effect transistors (FETs). The GaGeTe FETs display a p-type behavior with drain current modulation on the order of 103, hole mobility of 0.45 cm2 V−1 s−1, and photoreponsivity of 3.6 A W−1 at room temperature. These findings suggest that the layered GaGeTe is a promising 2D semiconductor for fabricating devices, such as transistors and photodetectors. Published by AIP Publishing. https://doi.org/10.1063/1.4998350

The two-dimensional layered materials are known to exhibit rich electronic, magnetic, and optical properties, such as superconductivity, ferromagnetism, semi-conductivity, and so on.1−5 The layered structure makes them possess appealing properties such as high transparency, flexibility, and ease of processing, which are very suitable for fabricating nanoelectronic/nanophotonic devices. For example, graphene, the first widely studied layered material, have been explored extensively for its potential use as transistors and photodetectors.6−9 However, graphene does not possess a band gap, which is essential for device applications. Hence, great efforts have been paid to explore functional 2D semiconductors with high carrier mobility, large tunable band gap, and high stability. In the past few years, a large number of 2D materials such as MoX2, WX2, GaX, TiX3, PtX2, and InX (X = S, Se, Te) have been explored for fabricating transistors due to their superior electrical properties.10−15 However, most of them exhibit n-type conductivity. GaSe, GaTe, and ReSe2 transistors were reported to be p-type conductivity, but its hole mobility is relatively low.14,16 Black phosphorus, which is one of few p-type semiconductors with high hole mobility, has long suffered from environmental instability.17,18 Thus, it is necessary to explore air-insensitive 2D semiconductors with p-type conductivity, from a point of view of designing PN junction based devices.

GaGeTe is an air-insensitive layered p-type semiconductor with a band gap of Eg = 1.12 eV.19 The hexagonal structure of GaGeTe consists of (Te-Ga-Ge-Ge-Ga-Te) layers, which are weakly coupled together with van der Waals interactions along the c-axis. In each layer, the Ge atoms form a hexagonal sheet sandwiched by two GaTe rings. The crystal symmetry is hexagonal, which belongs to the space group R-3m (No. 166), and the lattice parameters are a = 0.405 nm and c = 3.465 nm. The thickness of a single layer Te-Ga-Ge-Ge-Ga-Te is 1.15 nm.20 The vibrational modes of GaGeTe were investigated by Raman spectroscopy and match well with calculations.21 It was shown that bulk GaGeTe is a p-type semiconductor with hole mobility of 3.4 cm2 V−1 s−1.19,22 Although it has been synthesized for many years, investigations of electronic and photoelectronic properties of its 2D counterpart, which are indispensable for future PN junction device fabrication, are still lacking.

In this paper, we fabricated field effect transistors (FETs) using ultrathin GaGeTe flakes with typical thickness of nanometers, which are obtained from bulk crystal by Scotch tape method. The GaGeTe FETs display p-type conduction behavior with current on/off ratio of as high as 103 and room-temperature field-effect mobility of 0.45 cm2 V−1 s−1. Moreover, the photoreponsivity of the FETs are examined to be of 3.6 A W−1. Our findings suggest that GaGeTe is an attractive p-type 2D semiconductor, in particular, for the fabrication of nano-devices such as transistors and photodetectors.

First, we synthesized high-quality GaGeTe single crystals using the Bridgeman method.19 The starting materials of high-purity Ga ingot, Ge ingot, and Te powder (≥99.9%, Alfa) were weight stoichiometrically and vacuum-sealed (>10−5 Torr) into a quartz tube. The tube was heated at 980 °C for one day and cooled down slowly to 380 °C at a rate of 2 °C per hour, before the furnace was shut down. The as-grown crystals can be easily cleaved into sheets with typical dimensions of 5 × 5 × 1 mm3, which often contain small quantities of impurity phase GaTe.19 We carefully deal with the crystals by repeat exfoliation and mechanical cleavage to obtain pure GaGeTe crystals. The crystallinity was examined by a Rigaku-TRTR X-ray diffractometer using Cu-Kα radiation at room temperature. Figure 1 shows the X-ray diffraction (XRD) pattern of GaGeTe recorded at room temperature. All of the diffraction peaks well fit the (00l) hexagonal phase (space group R-3m), indicating the single crystalline character of the sample. The homogeneity and chemical compositions of the crystals were analyzed by energy dispersive x-ray spectroscopy (EDX), which is attached to the scanning electron microscopy. The atomic ratio of GaGeTe of the as-grown crystals (1.062:1:1.015) is very close to stoichiometry.
The crystal quality was further examined by high-resolution transmission electron microscopy (TEM). When the incident electron beam is perpendicular to the nanoflake, the selected area electron diffraction (SAED) pattern with respect to the zone axis [001] of GaGeTe can be obtained, as shown in the inset of Fig. 2. Diffraction spots of SAED patterns were indexed to hexagonal phase (space group R-3m). In the TEM image as shown in Fig. 2, one can clearly see an interplanar distance of 0.385 nm which corresponds to the (009) planes of GaGeTe. High-resolution TEM and SAED patterns confirmed the high crystallinity of our GaGeTe sample.

To investigate the electrical transport properties of GaGeTe thin films, we designed FETs based on isolated samples. Ultrathin GaGeTe flakes were obtained by the scotch tape-based mechanical exfoliation method from bulk single crystal. The flakes were transferred onto a Si wafer containing a 300 nm thick SiO₂ dielectric layer. The thicknesses of the flakes were determined by atomic force microscopy (AFM). The devices were fabricated by standard electron-beam lithography (EBL) and deposited Ti/Au (10 nm/80 nm) as contact electrodes. Figure 3(a) shows an atomic force microscope (AFM) image of a typical fabricated device. The thickness of the flake is about 6.4 nm. Electrical characterizations of the GaGeTe transistors were performed by using a semiconductor characterization system (4200SCS, Keithley) with a probe station (CRX-6.5K, Lake Shore). Figure 3(b) shows the output characteristics $I_{ds}-V_{ds}$ of the GaGeTe FET at different back-gate voltages ($V_{gs}$). All the $I_{ds}-V_{ds}$ characteristics display a linear behavior, suggesting that the Ti/Au electrodes provide good Ohmic contact to the GaGeTe flake. Moreover, the $I_{ds}-V_{ds}$ curves strongly depend on $V_{gs}$, that is, the slope of the $I_{ds}$-$V_{ds}$ curves increases with increasing negative $V_{gs}$. Figure 3(c) shows the transfer characteristic curves of the GaGeTe FET at room temperature, with drain-source voltages ranging from 0.1 V to 0.5 V. The $I_{ds}$-$V_{gs}$ curves indicate a p-type conduction behavior of the GaGeTe FET, since the conductance increases when the negative $V_{gs}$ is strengthened towards $-40$ V. Figure 3(d) re-plots the transfer characteristic curves of the GaGeTe FET at $V_{ds} = 0.5$ V in linear and logarithmic scale. For positive $V_{gs}$, the $I_{ds}$ through the FET is about 80 pA in the OFF state while for negative $V_{gs}$, the $I_{ds}$ reaches up to ~80 nA in the ON state, which gives an $I_{on}/I_{off}$ ratio of ~10³. Such an ON/OFF ratio is superior to some 2D FETs, and fulfills the requirements for CMOS logic devices. Noting that the maximum drain current $I_{ds}$ of our device has not yet been saturated due to the low dielectric constants and breakdown electric field of SiO₂, we believe that a higher drain current modulation could be achieved by using high-$k$ materials as gate dielectrics. The field-effect mobility ($\mu$) of the GaGeTe FET is estimated based on the following equation:

$$\mu = \frac{L}{W \times (\varepsilon_0 \varepsilon_r / d) \times V_{ds} \times \Delta I_{ds} / \Delta V_{gs}},$$

where $L/W$ is the channel length-to-width ratio and is ~0.5 for this study, $\varepsilon_0$ is the permittivity in vacuum, $d$ is the thickness of the dielectric layer (300 nm), and $\varepsilon_r$ is 3.9 for 300 nm.
SiO$_2$. The estimated field-effect mobility is 0.45 cm$^2$ V$^{-1}$ s$^{-1}$ and is nearly two orders of magnitude lower than the bulk of about 40 cm$^2$ V$^{-1}$ s$^{-1}$.

The determined subthreshold swing where $I_{ph}$ layers black phosphorus.4,26,27 has been fabricated and characterized at room temperature. We effective irradiated area on the device ($\frac{mW}{cm^2}$). Furthermore, we measured the current $I_{ds}$ at $V_{ds} = 2$ V under power intensity of 13.8 mW cm$^{-2}$ by intentionally switching on/off the incident light. In Fig. 4(b), we show the ON-OFF switching behavior. The current $I_{ds}$ is 1.6 nA and 4.1 nA in dark and under illumination, respectively. A photocurrent $I_{pb}$ of 2.5 nA was obtained by illuminated current minus dark current. The responsivity ($R$) is defined as photoresponsivity = $I_{pb}$/$P_{light}$, where $I_{pb}$ is the photogenerated current (2.5 nA in present case), $P_{light}$ is the incident laser power intensity, and $S$ is the effective irradiated area on the device (~5 $\mu$m$^2$). On the basis of the photocurrent generated by power intensity of 13.8 mW cm$^{-2}$, the estimated responsivity is 3.6 A W$^{-1}$. This value is higher than MoS$_2$ monolayer graphene, and few layers black phosphorus.3,26,27

In summary, ultrathin GaGeTe flake-based FETs have been fabricated and characterized at room temperature. We find a p-type semiconducting behavior with a hole mobility of 0.45 cm$^2$ V$^{-1}$ s$^{-1}$ and good ON/OFF current ratios up to 10$^3$, which is superior to many other reported 2D-based materials FETs. In addition, the GaGeTe FETs display a high photoresponsivity of 3.6 A W$^{-1}$. Our experimental results reveal the basic transport characteristics and potential applications of layered GaGeTe semiconductor as active elements in transistors and photodetectors.

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