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Ga₂O₃ field-effect-transistor-based solar-blind photodetector with fast response and high photo-to-dark current ratio

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Abstract—A high performance solar-blind photodetector based on Cr-doped gallium oxide (Ga₂O₃) has been fabricated. A 140-nm-thick Ga₂O₃ layer was mechanically exfoliated from bulk crystal. The photodetector was based on a field effect transistor structure, which showed a very high photo-to-dark current ratio larger than 10⁶ and excellent current saturation. When the photodetector was tested with a 254 nm ultra-violet light, the ratio of drain current with and without the UV light reached nearly six orders of magnitude. The dark current was as low as 5 pA. Furthermore, the current rise time and decay time were both about 25 ms. High responsivity of 4.79×10^5 A/W and external quantum efficiency of 2.34×10^6 also have been achieved at the same time.

Index Terms — gallium oxide (Ga₂O₃), field-effect-transistor (FET), solar-blind photodetector

I. INTRODUCTION

BECAUSE of the absence of radiation in the solar-blind region (240–280 nm) at the surface of the Earth, the so-called solar-blind photodetectors have advantages of high signal-to-noise ratios, low false alarm rates and ability of weak signal detection in many applications including ozone monitoring, flame detection, and missile tracking [1]–[5]. In recent years, a large variety of semiconductors like Al_xGa_{1-x}N, Zn_xMg_{1-x}O, and Zn_xGa_{1-x}O have been explored for solar-blind photodetectors [6, 7]. However, their complex growth processes and difficulties in achieving high material quality are still challenging.

The direct-band and wide-band gap (4.9 eV) of gallium oxide (Ga₂O₃) is ideal for solar-blind light sensing. Furthermore, the crystal growth of Ga₂O₃ bulk single crystals and the material quality have progressed rapidly in recent years [8, 9]. Compared with previous multi-element alloy materials [6, 7], Ga₂O₃ is not an alloy, and hence has a lower defect density which is critical to achieve a low dark current [10]. Ga₂O₃ active layers in

photodetectors have already been achieved via several methods, including hot-wall chemical vapor deposition [2], metal-organic vapor phase epitaxy [11], molecular beam epitaxy [12], magnetron sputtering [13, 14], and mechanical exfoliation from bulk single crystals [15, 16]. Among these methods, mechanical exfoliation ensures the highest film quality, and thus is highly beneficial for low defect density, low dark current, and high response to UV light [17]. Ga₂O₃ single crystals are layered materials, and there are two different Ga sites and two cleavage planes [(100) and (001)] [18]. Owing to such a cleavage nature, which is somewhat similar to two-dimensional materials, high quality Ga₂O₃ single crystalline films can be obtained by mechanical exfoliation from the bulk crystal [19].

Different types of photodetectors based on Ga₂O₃ have been demonstrated. This includes metal-semiconductor-metal structures [15, 17], Schottky barrier diodes [21], diamond/Ga₂O₃ heterojunctions [4], and graphene/Ga₂O₃/graphene hybrid structures [22]. Field-effect-transistors (FETs) are also often used as photodetectors due to their abilities of controlling the off current by gate bias. As a result, FET photodetectors can achieve very high photo-to-dark current ratio ($I_{\text{photo}}/I_{\text{dark}}$) and low dark current [23]. However, very few Ga₂O₃ solar-blind photodetectors with an FET structure have been reported, and their response speed still need to be further improved to meet the requirement of real applications [17].

In this work, we fabricated FET solar-blind photodetectors based on high quality Ga₂O₃ flake with a thickness of 142 nm, exfoliated from a Cr-doped Ga₂O₃ single crystal. It is reported that Cr dopant has advantage of modification optical properties of Ga₂O₃ [24]. The high crystal quality and the thin flake thickness contribute to the high performance of the photodetector which shows the current response time of about 25 ms, $I_{\text{photo}}/I_{\text{dark}}$ of 8×10^5 , and responsivity of 4.79×10^5 A/W.

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II. DEVICES FABRICATION AND MEASUREMENT

The schematic structure of Ga₂O₃-based FET photodetector is shown in Fig. 1(a). Figure 1(b) shows the top view scanning electron microscopy (SEM, FEI Nano 450) image of the device. The thickness of Ga₂O₃ channel layer in FET is 142 nm, as revealed by atomic force microscopy (AFM, Benyuan CSPM5500) and shown in Fig. 1(c). The Ga₂O₃ film was prepared by mechanically exfoliation from Cr-doped β -Ga₂O₃ single crystals wafer (5 mm $\times$ 10 mm $\times$ 5 mm) grown by edge-defined film-fed growth (EFG) method [9]. The electron carrier concentration in the Ga₂O₃ wafer is $\sim 1.0 \times 10^{18} \text{ cm}^{-3}$ according to the Hall measurement. After exfoliation, the Ga₂O₃ flakes were then transferred quickly to a heavily p⁺-doped Si wafer, with a 100-nm-thick thermally grown SiO₂ as the gate dielectric. To enhance the adhesion between Ga₂O₃ and Si substrate and reduce contaminants, the Si substrate was pretreated by oxygen plasma (ProCleaner™) for 3 minutes. Ti/Au (20/100 nm) as the source and drain electrodes were defined on both ends of the Ga₂O₃ flakes by photolithography, electron-beam evaporation, and lift-off. The source and drain contacts were improved by an inductive coupled plasma etch before electrodes deposition with the power, chamber pressure, gas flow, and etching time of 150 W, 20 mTorr, BCl₃/Ar (15 sccm/5 sccm) and 2 minutes, respectively. The channel length and width are 24 and 13 μm , respectively.

Fig. 1. (a) Schematic of the Ga₂O₃ FET, (b) SEM top view of the FET, (c) AFM height profile of the exfoliated Ga₂O₃, (d) AFM image of the Ga₂O₃ surface.

A source/measure unit semiconductor parameter analyzer (Keysight B2902A) was used to measure the electrical properties and time-dependent photo response of the device at room temperature. A 5.3 $\mu\text{W}/\text{cm}^2$ deep ultraviolet lamp with emission wavelength of 254 nm (UVCN, 10-04000) was used for solar-blind detection measurements.

III. RESULTS AND DISCUSSIONS

The exfoliated Ga₂O₃ flake has an ultra-smooth and uniform surface with a root mean square roughness of 0.28 nm, revealed by AFM, as shown in Fig. 1(d), indicating a high film surface quality. Figure 2(a) shows the X-ray diffraction spectra of the Ga₂O₃ wafer, illustrating the crystalline structure of the sample. The UV-visible optical transmittance spectra of the Ga₂O₃

wafer is shown in Fig. 2(b). The transmittance declines abruptly when the photon wavelength decreases from 360 to 260 nm and is close to zero when the wavelength is lower than 260 nm. By a standard fitting, the bandgap of the sample is estimated to be 4.72 eV, as shown in inset of Fig. 2(b). These results demonstrate that our Ga₂O₃ single crystal has an outstanding crystallization quality and good response to the deep UV light.

Fig. 2. X-ray diffraction scan (a) and transmittance spectrum (b) of the Ga₂O₃ crystal. Inset shows the bandgap of the Ga₂O₃ crystal.

The transfer curve with the drain current density, I_d , in both log-scale and linear-scale, of the Ga₂O₃ FET photodetector in dark is shown in Fig. 3(a). The drain voltage, V_d , was kept at 20 V during the measurement. The on/off current ratio of the FET is about 2.3×10^6 . The threshold voltage is about -7 V, as extracted from the linear extrapolation of the transfer curve in linear scale. The subthreshold threshold, SS , is about 0.63 V/dec, as extracted from the linear extrapolation of the transfer curve in log scale. The channel trap density D_t is extracted by evaluation of SS as follows [25]:

$$SS = \frac{k_B T}{e} \left(1 + \frac{q^2 D_t}{C_{ox}} \right) \ln 10 \quad (1)$$

where q is the electron charge, k_B is the Boltzmann constant, T is the absolute temperature, and C_{ox} is the gate capacitance per unit area. By Eq. (1), D_t is determined to be $2.06 \times 10^{12} \text{ cm}^{-2}$, and is larger than those of reported Ga₂O₃ FETs ($\sim 10^{11} \text{ cm}^{-2}$) [16, 26]. The high D_t leads to the relative high threshold voltage [27]. Figure 3(b) shows the output curves of the FET. The gate bias (V_g) varied from -14 to 10 V with a step of 4 V. It reveals a typical transistor performance with that I_d increased linearly at low V_d and saturated at high V_d with increased V_d . The output curves show clear saturation and pinch-off characteristics, indicating effective gate modulations in the n-type channel.

Fig. 3. Typical electrical transport properties of the Ga₂O₃ FET. (a) The transfer curve in log and linear scale with V_d of 20V, (b) The output curves with various V_g (from -14 to 10V).

Figure 4 exhibits the photo response properties of the Ga₂O₃ FET photodetector with UV light on and off. All these characterizations were carried at a pinch-off V_g of -20 V, and the drain current with light on and off is defined as I_{photo} and I_{dark} , respectively. The dependences of the drain current on light at different V_d are shown in Fig. 4(a). The drain current zooms

along with the light on and drops rapidly in pace with the light off at all V_d . Figure 4(b) shows I_{photo} and $I_{\text{photo}}/I_{\text{dark}}$ as functions of V_d . I_{photo} increases almost linearly with the increase of V_d . Figure 4 (b) shows almost linear dependences of I_{photo} and $I_{\text{photo}}/I_{\text{dark}}$ on V_d , demonstrating that I_{photo} and $I_{\text{photo}}/I_{\text{dark}}$ of the Ga_2O_3 FET photodetector can be tuned linearly by V_d . Here, for evaluating $I_{\text{photo}}/I_{\text{dark}}$ the same I_{dark} values of 5×10^{-12} A at various V_d was used, as 10^{-12} A already reaches our detection limit.

Fig. 4. (a) The current dependences of the Ga_2O_3 FET solar-blind photodetector on time with the light switching at different V_d , (b) I_{photo} and $I_{\text{photo}}/I_{\text{dark}}$ as functions of V_d . (c) The linear-scale current dependence on time with the light switching at V_d of 20 V with fittings of current rise and decay process, (d) The log-scale current dependence on time with the light switching at V_d of 20 V

TABLE I
SUMMARY OF KEY PHOTORESPONSE PARAMETERS OF THE FET SOLAR-BLIND PHOTODETECTOR

Parameters	Data
Photo-current (I_{photo}) [μA]	7.93
Response time τ_r/τ_d [s]	0.025 / 0.025
$I_{\text{photo}}/I_{\text{dark}}$	8×10^5
Responsivity (R) [A/W]	4.79×10^5
Detectivity (D^*) [Jones]	6.69×10^{14}
EQE [%]	2.34×10^6

The photodetector shows the highest $I_{\text{photo}}/I_{\text{dark}}$ with V_d of 20 V, as shown in Fig. 4(a). With V_d of 20 V, I_{photo} of the photodetector suddenly increased to 4 μA when the light turned on and increased further slowly with prolonged irradiation. Both rise time, τ_r , and decay time, τ_d , are about 25 ms by fittings [28], as shown in Fig. 4(c), and is lower than the reported values [17]. The reasons could be that the gate operation voltage applied on our Ga_2O_3 photodetector is much lower than its threshold voltage. It should be clarified that 25 ms is the shortest time step value of our source measurement unit under normal mode we used. Thus, the real τ_r and τ_d should be ≤ 25 ms. Figure 4(d) shows I_{photo} in log-scale with V_d of 20 V, illustrating a high $I_{\text{photo}}/I_{\text{dark}}$ of 8×10^5 . The strong generation of electron-hole pairs under the light irradiation and the low dark current $\sim 10^{-12}$ A contribute to such high $I_{\text{photo}}/I_{\text{dark}}$. It should be noticed that after tuning off the light, the current dropped rapidly back to $\sim 10^{-12}$ A, which is the noise floor of our measurement system. This is extremely beneficial for continuous and solar blind UV detection with high $I_{\text{photo}}/I_{\text{dark}}$ and low interference. The results

reveal that the Ga_2O_3 FET solar-blind photodetector can achieve high $I_{\text{photo}}/I_{\text{dark}}$ ratio and quick response.

The responsivity, R , detectivity, D^* , and external quantum efficiency, EQE, are the other key parameters to evaluate the performances of photodetectors. R and EQE evaluate the sensitivity of photodetectors [29], while D^* indicates the capability of photodetectors to detect small signals. R , was estimated to be 4.79×10^5 A/W using the equation $R = (I_{\text{photo}} - I_{\text{dark}})/S \cdot P_{\text{inc}}$ [30, 31], where S is the effective area of the channel, and P_{inc} is the illumination power. Besides, because the shot noise from the dark current dominates the total noise, D^* can be calculated by the equation $D^* = R \cdot S^{0.5}/(2eI_{\text{dark}})^{0.5}$ [30, 31], where e is the elementary charge. D^* of our device is $\sim 6.69 \times 10^{14}$, and is comparable to the reported value for Ga_2O_3 FET solar-blind photodetector. And it also exhibits a high EQE of 2.34×10^6 , estimated by the equation $\text{EQE} = hcR/(e\lambda)$ [32], where h and c are the Planck's constant and velocity of light, respectively. The photoresponse properties of the fabricated solar-blind photodetector are summarized in Table I.

IV. CONCLUSION

FET solar-blind photodetectors have been fabricated based on high quality quasi-two-dimensional single crystalline Ga_2O_3 flakes exfoliated from the bulk single crystal. The Ga_2O_3 FET show excellent photo response in the pinched off gate modulation state, with I_{photo} improves rapidly as the UV light on and drops down quickly as the UV light off. I_{photo} and $I_{\text{photo}}/I_{\text{dark}}$ of the photodetector can be tuned by the drain voltage. High $I_{\text{photo}}/I_{\text{dark}}$ of 8×10^5 , responsivity of 4.79×10^5 A/W, EQE of 2.34×10^6 , and quick response with I_{photo} rise and decay time of 25 ms were realized, indicating huge potential in solar-blind photodetector application field.

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