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Enhancement of near infrared light sensing using side-gate modulation

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ABSTRACT

The integration of nanostructures in electronic devices utilizes their unique quantum properties for realizing discrete measuring systems. Specifically, self-assembled organic monolayers and nanocrystals (NCs), together with bottom-up production methods, can lead to new types of electronic devices. In this work, we present a wavelength-tunable near-infrared detection device in which PbS NCs are used to create an optical gate for an AlGaAs/GaAs high electron mobility device. By integrating side gates, we were able to enhance light detection sensitivity by optimizing the conductivity of the channel. Both DC and AC modulations of the side gate were tested and compared in order to enhance the detector's signal–to-noise ratio (SNR). Higher harmonic signals of the side gate modulation supply additional information about the detection mechanism.

1. Introduction

Infrared (IR) detection capabilities have significant importance for various technologies such as thermal imaging, single photon detection, and biological imaging [1–3]. In recent years, major progress has been achieved in the integration of quantum confined structures for IR detection. Previous studies have demonstrated the use of carbon nanotubes, quantum wells, quantum dots (QD), and graphene in IR sensing applications [4–8]. The wavelength tunability of nanostructures and their self-assembly flexibility on diverse substrates make them excellent candidates for integration in detectors [9–11]. IR detector feasibility, based on several types of NCs has already been demonstrated [12–16]. For example, the energy gap size dependence and optical properties of PbS/PbSe QDs make them good candidates for IR detection [17–21]. NIR sensors were developed by coating PbS colloidal quantum dots (CQD) onto gold interdigitated electrodes, a responsivity of 10^3 A/W can be achieved [12]. Furthermore, it has been shown that by coating chemical vapor deposition (CVD)-grown graphene with PbS CQD, a NIR photodetector can be obtained with a responsivity of 10^7 A/W [21]. Additionally, PbS CQD-based photoconductors exhibit responsivity of 30 A/W and detectivity of $2 \cdot 10^{10}$ cmHz$^{1/2}$W at 1.3 μm [22]. Schottky barrier-based devices can be improved using CQD. For example, photodiodes based on the interface between a PbS CQD film and aluminum contact showed a high frequency response on the order of 10^4 Hz [14]. Improvement in detection performance can be achieved by introducing Ag NCs into the PbS CQD on the surface detection area, leading to an improvement factor of 2.4 in estimated device detectivity [23]. Lastly, energy traps in the PbS CQDs can be considered advantageous for improving response at sub-room temperatures [16].

GaAs is an attractive material for many applications such as light-emitting diodes, optical communication light detectors, field-effect transistors and integrated circuits [24,25]. Moreover, the GaAs technology allows the construction of high mobility conductive channels in the form of a quasi-two-dimensional electron gas (2DEG) for applications at high frequencies, such as the high electron mobility transistors (HEMTs) [26]. The production of HEMT structures involves epitaxial growth of GaAs-$Al_xGa_{1-x}As$ doped and undoped layers, usually using molecular beam epitaxy (MBE). Due to the differences between the layers' affinity, free electrons from the $Al_xGa_{1-x}As$ are transferred to the GaAs layer, resulting

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in the formation of the 2DEG channel. Because of the separation between the electrons and the donor impurities, the carrier mobility is enhanced. The reduction of scattering also results in high saturation velocity, and therefore, in an increase in operation frequencies [26,27]. These features are exploited using HEMT as light detector, gas detector, and terahertz devices [28–30]. We have previously shown that by coupling semiconductor QDs to HEMT devices, room temperature spectrally-tunable light detector can be realized [7,31,32]. QDs are unique in that their size, structure, and composition control their energy levels. Therefore, by modifying their composition or size under the proper synthesis conditions, it is possible to control their electronic and optical properties [9]. Adding dopants to QDs can increase their plasmonic absorption and shift their intra-band transition response to the infrared [33]. In the detector configuration, the QDs are used as an optical gate on top of a shallow 2DEG GaAs transistor. Their light absorbance results in a dipole moment that changes the level of current flowing through the device [34].

In a previous work, QDs acting as an optical gate on top a HEMT device demonstrated highly sensitive room temperature near-infrared (NIR) detection capabilities [7]. The high responsivity was achieved by physically narrowing the 2DEG channel. This detector was fabricated using standard optical lithography; therefore, the ability to decrease the channel width was limited. When the channel was narrowed below 2 μm, the roughness of the channel sidewalls enhanced electron scattering and therefore the total dark current noise. In the present work, we describe an alternative method of narrowing the channel in effect, using side gates. The ability to tune the sensitivity of a chemical sensor device using side gates has already been shown previously [35,36]. However, here we optimize the detectivity of a light sensor using both AC and DC side gate modulation. The primary advantages of this method as are follows: First, no lithography limitation exists in the fabrication process since the channel width is determined by the side gate voltage and not by the physical dimensions of the channel. The channel width can change continuously from open to fully closed. Second, the dark current noise is reduced due to the smooth electric potential. Finally, we can apply AC modulation to the side gate, further reducing noise at the detection frequency.

2. Materials and methods

In this work, we used two different PbS colloidal quantum dots: chloride-capped PbS (PbS/Cl) (prepared by E. Lifshitz's research group), and core PbS (purchased from CANGmbH Corp., CANdots, Germany), with diameters of 5.1 and 6.0 nm, respectively. The doped PbS/Cl were synthesized according to a previously published procedure with a slight modification [37]. Briefly, 3 mmol of $PbCl_2$ were dissolved in 7.5 ml oleylamine (OLA) in a three-necked flask, and degassed for 1 h at 100 °C. The solution was heated to 120 °C under nitrogen. In a separate flask, 5 mmol of sulfur were dissolved in 15 ml of OLA, and degassed for 1 h at 120 °C, followed by switching to nitrogen atmosphere. Next, 2.25 ml from the chalcogenide precursor solution were quickly injected into the Pb oleate solution under nitrogen. The temperature was then lowered to the growth temperature and maintained throughout the reaction until appropriate growth was obtained. After a specified time, the reaction mixture was cooled and centrifuged using toluene:oleic acid (OA) (in a ratio of 4:1) together with ethanol to isolate the QDs. Afterward, the QDs were dried and then re-dissolved in organic solvents such as hexane, toluene, or tetrachloroethylene (TCE) for further characterization.

The monolayer adsorption process of the PbS and PbS/Cl QDs was performed by linking molecules to the GaAs substrate, followed by QDs adsorption based of previous works [38,39,32]. As a linker we used HS−$(CH2)_9$−SH [1,9-nonane-dithiol (DT)]. The molecules were adsorbed in two steps. First, the GaAs was sonicated for 2 min in acetone solution, followed by 2 min in ethanol solutions. Then, the GaAs was etched for 20 s using 18.5% HCl. Finally, the GaAs was washed with double-distilled water (DDW). In the second step, the substrates were soaked in absolute ethanol for 20 min before they were immersed overnight in a 1 mM ethanol solution of the organic molecules. The excess organic molecules were rinsed from the surface by washing the sample with ethanol several times. The samples were then introduced into the QDs toluene solution for 3 h with stirring. In order to achieve a higher adsorption density, the samples were washed with toluene and immersed again in the QDs solution for another hour. The adsorption process was done under inert conditions at nitrogen atmosphere.

The structural design of the field effect transistor was based on the HETMOD modeling program acquired from IQE (USA). The HETMOD simulations solve the Poisson equation for the heterostructured energy band diagram under different conditions. The primary considerations for optimization were to achieve maximum sensitivity to small gate voltages at zero bias, and to avoid the formation of parasitic conductive channels. The HEMT device fabrication process and the method to improve sensitivity by reducing noise has been described in detail in previous works [7,32]. Here, we used the same layered structure with minor thickness modifications to optimize the response. In addition, a top layer of 30 nm n-type GaAs was added to the structure to improve the contact resistances. To reduce the Schottky noise even further, we reduced the distance between the source and the drain to appx. 500 nm in length and 1 μm in width using e-beam lithography, resulting in a detector with decreased resistance. Prior to the deposition of the gate electrodes, a 30 nm layer of Al_2O_3 was deposited using plasma atomic layer deposition (ALD). Two side gate electrodes of 20 nm Ti followed by a 100 nm-layer of Au were evaporated by e-beam with final dimensions of 6 μm × 2 μm overlapping the channel edges and 4 μm apart. Finally, the active detector area window of 2 μm × 3 μmwas opened in the Al_2O_3 layer using buffered HF (6:1) etch. The resulting detectors showed an ohmic behavior with a resistance of about 1 KΩ. The fabrication process yield was about 90%.

The electrical measurements were performed under inert conditions by applying two gating modes: fixed (namely, DC) and alternating (or AC) side gate modulations. In the DC measurements, the gate voltage was applied with respect to the drain contact by an external power supply (Agilent E6331A). The optical signal was modulated using a halogen light source with a chopper at a frequency of 180 Hz. The signal was obtained using a lock-in amplifier (Stanford SR830). In the case of AC gate measurements, the applied voltage was modulated between the two side gates, across the channel, using the lock-in amplifier. In both cases, the source-drain voltage and current were applied and measured, respectively, by a 2401 Keithley source-meter unit. The electrical circuit for both cases is presented in Fig. 1c. The spectral measurements were performed using a halogen source with an IR monochromator. Noise analyses were carried out using a fixed 980 nm light source using a CW diode laser. To reduce light power and compare between different wavelength responses, we used a set of filters and attenuators.

3. Results and discussion

In the current research, PbS QDs were used as a NIR optical gate on top of a HEMT device in order to generate a wavelength-tunable sensitive room temperature detector. The QDs were adsorbed on top the device surface using a self-assembled monolayer (SAM) of DT molecules. As a result of the illumination, excited holes were transferred to the HEMT surface states via the SAM. The induced