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Highly sensitive room temperature infrared hybrid organic-nanocrystal detector

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ABSTRACT

In this paper we demonstrate a very sensitive near-infrared light detector device based on InAs nano crystals (NCs) acting as an optical gate on top of a high-mobility shallow two-dimensional electron gas channel. The ability to integrate electronics with the NCs using both top-down and bottom-up approaches allows to utilize the NCs unique quantum properties for future optoelectronic devices. We employ wet chemistry to self-assemble the organic monolayers and the NCs on top of the field effect transistor. By using shallow and very narrow channel, the device's quantum efficiency can go as high as 10^6 V/W at room temperature, with a signal-to-noise ratio that enables sensitivity for very low photon power. We find that our experimental results are compatible with simulation. Lastly, the route to advance to the single photon detection limit is discussed.

1. Introduction

Semiconductor GaAs-based devices are used for light-emitting diodes (LEDs) in optical communications and control systems, field effect transistors (FETs), and integrated circuits [1–5]. These devices utilize two main advantages of the GaAs/AlGaAs system: GaAs devices' high mobility [6], and the fact that complicated band gap engineering can be easily accomplished by epitaxial growth [7].

Optoelectronic devices requiring high speed, together with photon counting abilities, have been extensively studied in recent years [8–10]. Most of the studies focus on the visible range wavelengths [11–13]. The development of a fast and sensitive room temperature detector in the infrared (IR) region has been elusive. Graphene grown by chemical vapor deposition has shown a very fast response but low responsivity of the order of 0.01 A/W measured at as low as 20 K in the IR region [14]. While reduced graphene oxide showed improved responsivity of ~0.7 A/W in the infrared photoresponses [15], its main drawback lies in its slow response time of around 2 s. Another category of sensitive photon counting detectors is the InGaAs avalanche photon diodes (APD). While these detectors exhibit high performance at slightly cooled temperatures of around 250 K in the short wave IR range (incident photon counting at 1500 nm wavelength was demonstrated) [16,17,8], the cooling complicates the system, and the wavelength control is somewhat limited.

By coupling semiconductor nanocrystals (NCs), often called quantum dots, to a field effect transistor (FET), we have previously shown that a room temperature spectrally tunable light detector can be realized [18–20]. Nano-structures are unique since their energy levels depend on their size, structure, and composition. Hence, it is possible to control their electronic and optical properties and in particular, the absorption and/or emission wavelengths by modifying their composition or sizes [21–23]. When the NCs absorb light, charge or energy, separation occurs that creates a dipole moment that changes the current flowing through the transistor.

In this work we present a highly sensitive near-infrared light detector device based on InAs NCs acting as an optical gate on top of a high-mobility shallow two-dimensional electron gas channel. Our basic device's platform uses the GaAs/AlGaAs system's main advantages to develop a shallow field effect transistor together with adsorbed nano particles generating a highly sensitive room temperature detector. The selective absorbance of the nano particles enables control over quantum properties in the *XY* plane [24], whereas the epitaxial growth controls the *Z* direction. This approach provides many opportunities and may open the way for developing new photon counting devices. The response spectrum can be tuned by changing the size, shape, or composition of the NCs.

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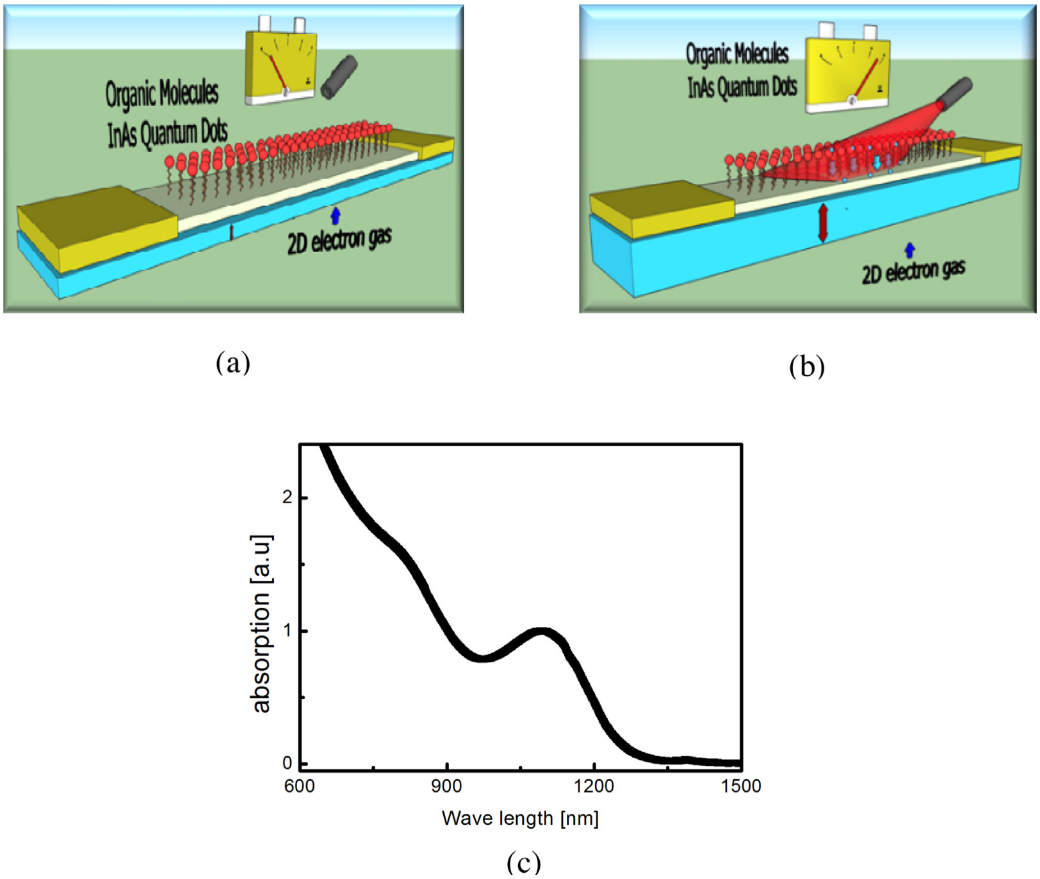

(a) (b) (c)

Fig. 1. (a) The hybrid organic NCs' detector, based on GaAs high electron mobility transistor with NCs acting as a gate. (b) The NCs' light absorption induces a change in the 2DEG width, consequently, changing the high electron mobility transistor channel's conductivity. (c) Absorption spectrum of InAs NCs in a solution; the peak maximum is approximately at 1100 nm.

The high sensitivity is achieved by obtaining a large gain for the on state. The organic molecules' couplers were chosen to act mainly as a tunnel barrier between the excited state in the NCs and the device surface states, thus reducing their dependence on the temperature. By optimizing the FET structure to operate at lower temperatures several parameters can be improved such as signal-to-noise ratio (SNR), Johnson noise and mobility, thus improving dramatically the detector's performance.

The schematics of our experimental device are shown in Fig. 1a. Self-assembled monolayers (SAMs) are used for linking the NCs to the solid-state device. In this specific case, colloidal InAs NCs were covalently adsorbed on a SAM that linked them to the surface of a 2DEG GaAs/AlGaAs field effect transistor. The device is then illuminated by a laser with energies smaller than the GaAs energy band gap and larger than the InAs energy gap (Fig. 1c). Under illumination, the photo-excited holes are transferred to the transistor surface states via the SAM. The induced change in the surface potential bends the surface energy levels, thereby increasing the 2DEG electron's density. Therefore, by measuring the enhanced conductivity of the transistor channel (Fig. 1b), sub GaAs band-gap illumination can be detected [18,19]. In all the devices used here, the above mechanism was confirmed by measuring a positive jump in the DC response under light illumination, a jump that was absent without the NCs.

The change in the FET current can be larger by several orders of magnitude than the number of electrons photoexcited in the NCs. This results from the intrinsic gain mechanism underlying the transistor. In most devices the large possible gain does not greatly improve the signal-to-noise ratio. The small difference created in the gate voltage, when photons are absorbed, does not significantly change the gain of the on or off states. This is not true, however, if the channel can be opened or closed by a single event. By narrowing the channel the sensitivity increases and the signal-to-noise ratio can improve. Controlled reduction in the transistor conducting channel can be achieved using etching and a side gate. By approaching the 1D conduction limit in the sub threshold regime, a small surface dipole field is enough to induce large conductivity, which, consequently, can dramatically change the gain. At the 1D limit, where only one conducting channel is available one loses the possibility of counting the photons and consequently and the detector's noise increases for high photon flux.

2. Materials and methods

The InAs nanocrystals were linked to the GaAs substrate using HS–$(CH_2)_9$–SH [1,9-nonane-dithiol (DT)] molecules. Samples were prepared in three steps: First, the GaAs were sonicated in acetone and ethanol solutions for 2 min each. Then the GaAs were etched for 5 s with 2% HF, washed with double-distilled water (DDW), etched with NH_4OH for 30 s, and finally washed with DDW. In the second step the substrates were soaked in absolute ethanol for 20 min before they were immersed into a 1 mM ethanol solution of the organic molecule (the "linker") overnight. The excess of organic molecules was then rinsed from the surface by washing the sample with ethanol several times. In the last step the samples were dried under nitrogen and introduced into a toluene solution containing the NCs for 3 h. In order to achieve higher coverage and more layers in some of the samples, consecutive coating processes were carried out, where the samples were immersed for 3 h alternatively in the linker and in the NC solutions.