Single-photon detection using a semiconductor quantum dot, optically gated, field-effect transistor

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Abstract: We demonstrate the operation of a novel quantum dot, optically gated, field-effect transistor as a photon detector. The device is shown to exhibit single-photon sensitivity, a linear response, and an internal quantum efficiency of ~73 %.

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The ability to detect light at the single-photon level is a crucial component in the burgeoning areas of quantum information and quantum cryptography, as well as in the advancement of medical diagnosis and imaging, single-molecule spectroscopy, quantum optics, and other low-light measurements. Field-effect transistor devices sensitive to single photons have been demonstrated [1-3] and are attractive detectors due to their potential for high speeds and low dark counts and their ability to preserve the quantum mechanical spin information of photo-generated carriers. However, single-photon detectors of this type have to date exhibited relatively low quantum efficiency (QE). Here we present a novel semiconductor quantum dot, optically gated, field-effect transistor (QDOGFET) design and show that the detector is capable of single-photon sensitivity while exhibiting a high internal QE.

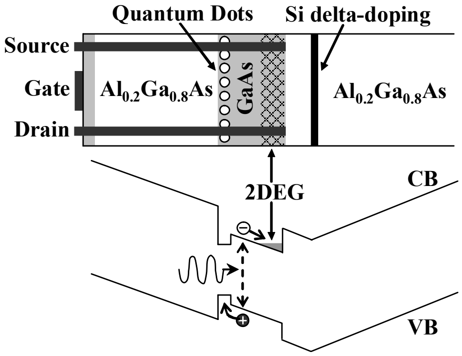

Fig. 1. Schematic diagrams of the composition and band structure of the QDOGFET. CB and VB denote the conduction and valence bands, respectively.

The QDOGFET consists of a GaAs/$Al_{0.2}Ga_{0.8}As$ modulation-doped field-effect transistor with a layer of InGaAs quantum dots (QDs) positioned relative to the high-mobility two-dimensional electron gas (2DEG) as illustrated in Fig. 1. The device is designed to efficiently detect photons absorbed in the GaAs region of the heterostructure and operates in the following way. A photon absorbed in the GaAs layer creates an electron-hole pair. With a reverse bias applied to the gate, the hole is swept by the internal electric field toward the QD layer, where it is trapped by a dot, while the electron is swept in the opposite direction, where it joins the 2DEG. Confined to the QD, the positively charged hole screens the internal electric field for as long as the hole is stored in the dot. The reduction of the internal electric field causes an increase in the conductance of the channel. Over time, the charging of the QDs caused by even a single carrier results in a large change in the cumulative charge transferred in the channel (a small change in the channel current integrated for a long time). This photoconductive gain makes the device very sensitive to illumination with light of the appropriate photon energy. Because the structure is specially designed to direct photo-excited holes toward the QDs, the device has the potential for achieving high QE.

We investigated the operation of the photodetector by illuminating the gated area of the QDOGFET channel (2 μm × 3 μm active region) with highly attenuated laser pulses of photon energy (1.54 eV) just above the bandedge of the GaAs layer and by monitoring the change in the source-drain current (I_{sd}) as a function of time. The device was cooled to <10 K and externally biased for all the measurements presented here. After each pulse, the device was reset by temporarily forward biasing the structure. This resulted in the flow of electrons toward the QD layer, where they discharged the dots by recombining with the trapped holes. In Figs. 2(a) and 2(b) the results of illuminating the photodetector with 5 μs laser pulses are shown. For these measurements, the laser pulses were attenuated such that on average ~2.4 photons were absorbed in the GaAs channel region per pulse.

In Fig. 2(a), the average temporal response of the detector with and without illumination is shown. Here *t*=0 is defined by the arrival of the laser pulse, and the average is taken over 437 single-shot measurements. Notice the well-defined step in I_{sd} occurring at *t*=0 coinciding with illumination. This laser-induced change in I_{sd} persists until the device is reset 500 ms later. The mean step height caused by the laser pulses is found to be ~295 pA.

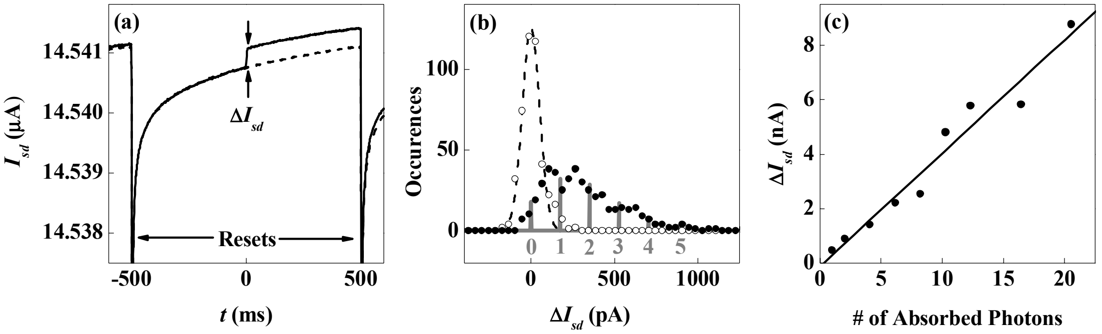

Fig. 2. (a) Average photo-response of the QDOGFET detector for a laser pulse arriving at *t*=0 (solid) and in the absence of laser illumination (dashed). (b) Occurrence distribution of the measured step heights ΔI_{sd} with (solid circles) and without (open circles) laser illumination. The solid gray curve is a Poisson distribution for 1.8 mean photoevents (gray numbers indicate individual events), and the dashed curve is a Gaussian fit to the null-step data. (c) Average step height as a function of the mean number of photons absorbed in the GaAs layer.

The distribution of the step heights ΔI_{sd} measured for the individual data sets averaged in part (a) is plotted in Fig. 2(b). The filled circles correspond to step heights observed with laser illumination, while the open circles correspond to those measured at *t*=0 with the laser pulses blocked prior to the detector. The full-width at the 1/*e* points of a Gaussian fit to the null-step data is ~147 pA, representing the limit on how well we can currently resolve the height of a single step. Notice that the distribution of step heights observed with illumination is asymmetrically distributed about the mean, characteristic of a Poisson distribution of a small number of laser-induced photoevents. A calculation of $(\mu/\sigma)^2$, where μ is the mean step height and σ is the standard deviation of the distribution, yields ~1.8 photoevents, providing a measure of the number of holes trapped by the QDs. The data indicate that each trapped hole changes I_{sd} by ~164 pA, indicating that the resolution of our detector system is ~1 photon. In addition, by evaluating the ratio of the number of trapped holes to the number of average photons absorbed in the active region of the device (~2.4) we obtain an internal QE of ~73 % for the detector.

Also plotted in Fig. 2(b) is the ideal Poisson distribution characteristic of 1.8 photoevents. Here, the change in I_{sd} per trapped hole was taken to be 176 pA, a value determined for our device dimensions from a simple parallel plate capacitor model [4]. This value agrees very well with our experimental finding and is the spacing between the individual photoevents (numbered in gray) of the ideal distribution. Notice that the experimental data approximate the envelope of the Poisson distribution, as one would expect given the ~1 photon resolution of our system.

Finally, the linearity of the device was demonstrated by making additional measurements using pulses of various photon densities. Typical results of these measurements are shown in Fig. 2(c). Here, the mean step height induced by laser illumination is plotted as a function of the number of photons absorbed in the GaAs layer. Notice the measured step height is linear with the number of absorbed photons, a desired characteristic for a photon-number-resolving detector. [m1]

In conclusion, we have demonstrated the operation of a novel QDOGFET photon detector. The device exhibits an internal QE of ~73 %, a linear response, and light level resolution on the order of a photon. It is important to note that while the internal QE of the detector is quite high, the device's overall QE is ~4 % (~50 % gate transmission and ~10 % absorption). It should be possible to construct devices that exhibit detection efficiencies that approach their internal QEs, however, by optimizing the thickness of the absorption region and by growing the devices inside resonant cavities. In addition, we expect much improved light level resolution by fabricating devices with smaller active areas, making the detectors potentially suitable for high efficiency photon counting. Support for this project has been provided by DTO.

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