Detection of single photons using a field-effect transistor gated by a layer of quantum dots

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We demonstrate that the conductance of a field-effect transistor (FET) gated by a layer of nanometer-sized quantum dots is sensitive to the absorption of single photons. Rather than relying upon an avalanche process, as in conventional semiconductor single-photon detectors, the gain in this device derives from the fact that the conductivity of the FET channel is very sensitive to the photoexcited charge trapped in the dots. This phenomenon may allow a type of three-terminal single-photon detector to be developed based upon FET technology. © 2000 American Institute of Physics. [S0003-6951(00)01525-4]

Time-resolved single-photon detection is required for such diverse applications as medical diagnosis and imaging, chemical analysis, laser ranging, and materials characterization.\textsuperscript{1} Photonic technology is also important for future applications in optical quantum cryptography and computing. Conventionally, single photons are detected by multiplication of a photogenerated carrier by an avalanche process, either in a vacuum photomultiplier tube, or, in the case of the semiconductor avalanche photodiode, a reverse-biased junction (see, for example, Refs. 1–3). Here, we propose and demonstrate detection of single photons based upon an entirely different principle using a field-effect transistor (FET) containing quantum dots.

Self-organizing growth techniques, based upon carefully controlled strained layer epitaxy, allow the formation of a high density of quantum dots with nanometer dimensions and relatively homogeneous size distribution. A particularly attractive aspect of this technique is that it can be used to produce quantum-dot layers within an epitaxially grown device structure. It has been shown that such a layer of self-assembled quantum dots can radically alter the transport properties of a nearby two-dimensional electron gas (2DEG).\textsuperscript{4–6} Under illumination the quantum dots can trap photoexcited carriers, providing the possibility of using such dots as an optically addressed data storage medium.\textsuperscript{7–11} Such structures have also been demonstrated as nonquantum detectors of midinfrared radiation through excitation of the 2DEG in the GaAs channel.\textsuperscript{12}

Since there are bound states of the quantum dots lying to lower energy than the conduction-band edge of the GaAs channel, each dot traps several excess electrons. This negative charge induces a repulsive potential, depleting the 2DEG electron densities for which the 2DEG has a low but finite conductivity, the channel current is extremely sensitive to the charge trapped in the dots. Carriers photoexcited by incident light are captured by the dots, thereby altering the conductivity of the 2DEG. Thus, if the active area of the device contains a sufficiently small number of quantum dots, it could be possible to detect a change in the 2DEG conductance due to capture of a single photoexcited carrier by a dot.

The layers were grown by molecular-beam epitaxy on a (100)-oriented GaAs substrate and consist of GaAs buffer, 250 nm Al\textsubscript{0.33}Ga\textsubscript{0.67}As, 40 nm Si-doped 10\textsuperscript{18} cm\textsuperscript{-3} Al\textsubscript{0.33}Ga\textsubscript{0.67}As, 40 nm Al\textsubscript{0.33}Ga\textsubscript{0.67}As, 20 nm GaAs channel, 10 nm Al\textsubscript{0.33}Ga\textsubscript{0.67}As, 2 nm GaAs, 1.7 ML InAs which forms the quantum dot layer, 50 nm Al\textsubscript{0.33}Ga\textsubscript{0.67}As, 30 nm Al\textsubscript{0.33}Ga\textsubscript{0.67}As (Si-doped 10\textsuperscript{18} cm\textsuperscript{-3}), and 10 nm GaAs. Photoluminescence spectra taken on the wafer display the typical signature of a high-quality InAs quantum-dot layer, with several peaks between 1.1 and 1.3 eV due to recombinations of electrons and holes in different states confined in the dots.

We also studied several other samples with closely spaced

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A mesa was etched using photolithography to confine the conducting channel to a narrow bar measuring 2 × 20 μm. Source and drain NiAuGe Ohmic contacts (not shown in Fig. 1) were made to the electron channel on either end of the bar. A semitransparent Schottky contact, consisting of a 7-nm-thick layer of NiCr, was defined across the center of the bar using e-beam lithography. Structures were prepared with different gate lengths measured along the long axis of the mesa of between 1 and 10 μm. Larger Hall bars were also fabricated for characterization of the channel density and mobility. All the measurements presented here were recorded with a sample temperature of 4 K, although similar behavior was also observed at 77 K.

Figure 2 plots the gate–drain bias dependence of the source–drain conductance of a FET with a 2-μm-wide mesa and 1-μm-long gate. Following strong illumination of the device with a red light-emitting diode (LED) for a few seconds, the conductance follows the upper curve. After the gate voltage has been swept to +0.8 V, so that a small current flows between the 2DEG and gate, the conductance follows the lower curve on the reverse sweep. Thus, over a wide range of gate biases there are two possible values for the conductance, set by illumination and applied gate bias.

Decreasing the gate bias reduces the density of the 2DEG under the gate area. Below some critical density, electrons localize in potential minima within the channel leading to a sharp decrease in the 2DEG mobility and thus conductivity. The mobility of the 2DEG layer in this structure is limited by the spatially inhomogeneous potential induced by the nearby negatively charged quantum-dot layer. Illumination creates electron–hole pairs within the structure. Holes photoexcited in the quantum well are swept by the internal electric fields towards the negatively charged dots. After tunneling into the quantum dot they recombine with a excess electrons trapped there. Meanwhile, the photoexcited electron remains in the 2DEG layer. Thus, illumination reduces the number of electrons trapped within the dots, with a corresponding increase in the 2DEG density. This is evidenced by magnetotransport measurements made on large gate area devices, which show that illumination increases the 2DEG density by a few 10¹⁰ cm⁻². This has the effect of smoothing the 2DEG potential, explaining why the conductance edge shifts to a more negative gate bias (i.e., lower 2DEG density) after illumination. The dots are recharged under forward gate bias (the “reset” gate bias), thus returning the conduction edge to the same gate bias, as it was prior to the illumination.

Figure 3 demonstrates detection of single photons by the device. The curve plots the change in conductance of the 2DEG with time under very weak illumination by a LED passing a current of 2 μA. The photon flux incident on the...
single-photon events. From the best fit strating that the steps in the conductivity are triggered by approximately linearly with the incident photon flux, demon-
demonstrates that the photon detection rate increases ap-
rate, determined assuming Poissonian statistics. Figure 4 data, we determine the quantum efficiency for the device under these measurement conditions to be 0.48%. However, this value is limited by the fact that most of the photons incident on the device pass through the thin quantum well and dot layers and are absorbed by the substrate. By introducing thicker absorbing layers into the active region of the device, and replacing the semireflective NiCr gate layer with a doped semiconductor layer, we can expect an increase in quantum efficiency by two orders of magnitude.

The results presented here show that a FET containing a layer of quantum dots can detect single photons. Although the lock-in techniques used here can only resolve photon arrival times on second time scales, we can expect the detector, which is based on a short-gate FET, to show a fast instru-
ment response. It should also be possible to enhance the quantum efficiency over the value in the present device by increasing the thickness of the absorbing layer feeding the quantum dots.

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13 The fact that the error seems to be overestimated may be explained by the noise from the LED being sub-Poissonian; see, for example, M. Kobayashi, M. Kohno, Y. Kadoya, M. Yamanishi, J. Abe, and T. Hirano, Appl. Phys. Lett. 72, 284 (1998).