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Infrared phototransistor using capacitively coupled two-dimensional electron gas layers

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A narrow-band infrared phototransistor (14.8 μm) is designed and realized based on a GaAs/AlGaAs double-layer structure. An isolated island formed from the first quantum well (QW) works as a gate, which is capacitively coupled to the remote two-dimensional electron gas (2DEG) layer working as the source/drain channel. Incident radiation excites the intersubband transition within the isolated QW island. Excited electrons tunnel out of the QW causing it to positively charge up. This affects the conductance of the remote 2DEG channel, yielding detectable photosignals. The present detection mechanism makes it possible to design semiconductor infrared detectors with higher sensitivities along with custom designed tunability. The mechanism also holds potentiality of single-photon detection in the infrared region. © *2005 American Institute of Physics*.

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Semiconductor quantum wells (QWs) provide us with an attractive system for designing detectors of infrared radiation (IR) because the energy spacing between two-dimensional subbands in the QWs is readily designed in the infrared spectral range by choosing material parameters including the well width. The most extensive studies have been carried out on QW infrared photodetectors,[1,2] in which electrons are photoexcited in multiple QWs to yield photocurrent that is driven vertically to the QWs. Vertical photocurrents, however, intrinsically suffer from relatively low electron mobility, leading to limited detector performance. Lee *et al.*[3] studied lateral photocurrents in GaAs QWs that are induced by exciting self-assembled quantum dots embedded in the QWs. In all of these detection schemes, however, photoexcited electrons yield the photocurrent to be detected. Because of the lack of a built-in amplification mechanism, the detection sensitivity may hardly reach a single-photon level, which has been achieved both in the shorter-[4–7] and the longer-[8,9] wavelength ranges.

In this letter, we propose and demonstrate a different detection scheme, in which an electrically isolated island of a QW is photoexcited to serve as a gate to a remote two-dimensional electron gas (2DEG) conducting channel. As schematically shown in Fig. 1, photoexcited electrons escape the isolated QW island leaving holes behind. The photoelectrons are driven to the 2DEG conducting channel yielding photocurrents. Another effect larger than this direct photocurrent arises from the positive charge left on the QW island, which, through capacitive coupling increases the electron density in the 2DEG channel and thus its conductance. The effect persists until the excited electrons recombine with holes in the isolated island, serving as an amplification mechanism. Our detector is thus a charge-sensitive phototransistor, in which a QW island works as a photosensitive floating gate. This scheme is reminiscent of a photosensitive field-effect transistor in the near-infrared range,[6] where single photons have been detected by utilizing quantum dots that trap charges created via band-gap photoexitation.

To realize the scheme in the above, we fabricate devices [Fig. 2(a)] in a GaAs/AlGaAs modulation doped heterostructure crystal containing a GaAs QW and an inverse heterostructure as shown in Fig. 2(b). The layers are grown by molecular-beam expitaxy on an *n*-type conducting GaAs substrate: They consist of a 1 μm thick buffer layer (AlGaAs/AlAs superlattices), a 30 nm $Al_{0.3}Ga_{0.7}As$ spacer layer, a 50 nm GaAs layer, a 100 nm composition-graded $Al_xGa_{1-x}As$ ($x=0.01\rightarrow 0.1$) barrier layer, a 2 nm $Al_{0.2}Ga_{0.8}As$ tunnel barrier, a 10 nm GaAs QW layer, a 85 nm $Al_{0.3}Ga_{0.7}As$ barrier layer, and a 10 nm GaAs cap layer. Electrons in the lower inverse heterostrucure are supplied by a δ-doping (Si:5×10^{11} cm^{-2}) at 30 nm below the heterointerface, and those in the upper QW by the δ-doping (Si:8×10^{11} cm^{-2}) at 25 nm above the upper heterointerface of QW. Two additional δ-doping layers (both 1×10^{12} cm^{-2} Si) are placed at 25 nm and at 60 nm below the top surface for compensating surface charge. Shubnikov–de Haas and capacitance-voltage measurements show that the electron

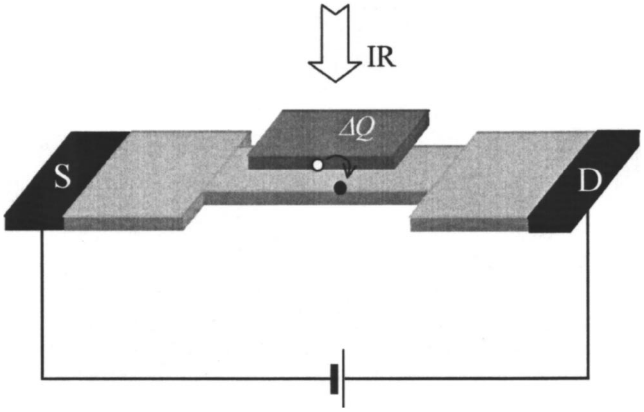

FIG. 1. Schematic representation of the detector.

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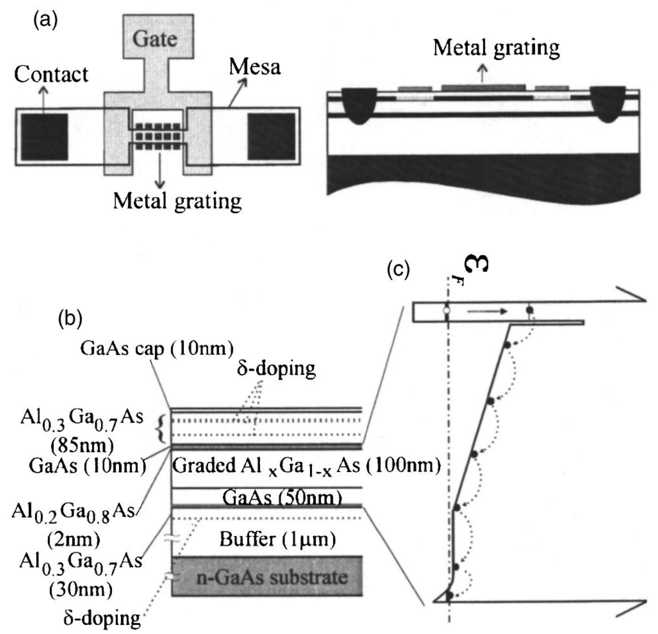

FIG. 2. (a) Top view (left panel) and cross-sectional view (right panel) of the device. (b) GaAs/AlGaAs heterostructure. (c) Schematic representation of the energy diagram.

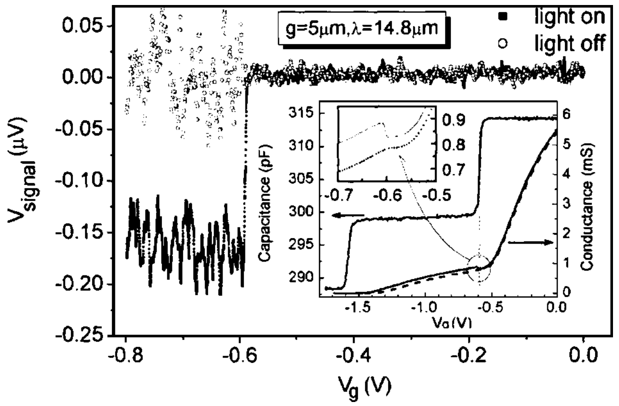

FIG. 3. Solid dots represent photosignal against the gate voltage for $g=5$ μm and $\lambda=14.8$ μm. White dots show reference data taken without the radiation from the globar. The inset shows the capacitance and the conductance against the gate voltage, both with solid lines. For the conductance, reference data taken in the complete dark (without 300 K-black-body radiation) is represented with the dotted line. The smaller panel in the inset is a blow up of the conductance curves around $V_g=-0.59$ V.

density and the electron mobility of the upper QW are 2.9×10^{11} cm^{-2} and 3.7×10^{5} cm^{2} V^{-1} s^{-1}, and those of the lower 2DEG layer are 2.1×10^{11} cm^{-2} and 9.7×10^{4} cm^{2} V^{-1} s^{-1}, both at 4.2 K.

The device is fabricated by a standard technique of electron-beam lithography. A two-terminal conductor with a constricted region of a 50 μm width and a 200 μm length is formed by wet mesa etching of 80 nm depth. Ohmic contacts are prepared by alloying of a 200 nm thick AuGe/Ni layer. Two front cross gates sandwiching the constricted region are formed by depositing a metal layer (15 nm Ti/65 nm Au), so that in a negative bias condition the upper QW in the constricted region is electrically isolated. Normal components of the optical electric field to the QW plane are needed to cause inter-subband transition in the QW. To create the vertical components for normal incident IR radiation, a metal grating consisting of an array of square metal pads is deposited,[1,10] where the ratio of the open to the metal-pad areas is fixed to unity. Different devices with grating periods of $g=2.5$ μm, 5 μm, and 7.5 μm are prepared.

The upper QW is so designed that the energy spacing between the ground subband and the first excited subband is $E_{01}=90$ meV (wavelength of 14.0 μm). When IR light with the photon energy of E_{01} is incident on the isolated QW, electrons are excited to the first excited subband, where the thin tunnel barrier allows those excited electrons to rapidly escape to the lower barrier layer as schematically depicted in Fig. 2(c). The electrons, having tunneled out of the QW, fall down the electrostatic potential slope in the graded barrier layer until they eventually reach the 2DEG channel to be absorbed there. This causes the isolated QW island to positively charge up. Through capacitive coupling, the pile-up positive charge in the isolated island increases the electron density of the lower 2DEG channel leading to an increase in conductance.

All of the experiments are carried out at $T=4.2$ K and with the n-GaAs substrate grounded to the Earth. As shown in the inset of Fig. 3, the capacitance between the front gates and the QW/2DEG layers decreases step wise at $V_g=-0.59$ V and at $V_g=-1.6$ V by decreasing the gate bias voltage V_g. This indicates that the upper QW in the regions underneath the gates is depleted below $V_g=-0.59$ V forming the isolated island in the constricted region, and the lower 2DEG channel underneath the gates is depleted at $V_g=-1.6$ V. This is reassured by the conductance curve shown together in the inset of Fig. 3, where the conductance decreases with decreasing V_g, changing the slope of its decrease at $V_g=-0.59$ V and completely vanishing at $V_g=-1.6$ V.

A globar is used as the source of IR radiation. The radiation from the globar is chopped at a low frequency (6 Hz), passed through a grating monochromator and guided to the device through an optical system consisting of mirrors, metal light pipes, and KRS-5 lenses. A black polyethylene film is placed at 4.2 K. A dc current of 30 μA is passed through the device and the voltage drop across the device is studied. The photosignal is detected via a standard modulation technique using a lock-in amplifier. For later discussion, we mention that not only the radiation from the globar but also 300 K-black-body radiation arising from room-temperature optical components (the chopper, the monochromator grating, mirrors, and metal-pipe walls, etc.) reaches the device in our optical scheme.

Typical photosignal ($\lambda=14.8$ μm) is shown in Fig. 3 for a device of $g=5$ μm. The photosignal (solid dots) is found to occur when V_g decreases below $V_g=-0.59$ V, viz., when the QW island is electrically isolated. The polarity corresponds to increase of conductance due to the illumination. These characteristics are a consequence that the QW island is positively charged up by IR illumination only when it is electrically isolated from the source/drain contacts and that the positive charge on the isolated QW island is sensed by the 2DEG channel through an increase in the electron density.

The excitation spectrum taken in the devices of $g=2.5$ μm, 5 μm, and 7.5 μm is displayed in Fig. 4, where V_g is fixed at $V_g=-0.7$ V for all of the devices. The photoresponse takes a sharp maximum at about $\lambda=14.8$ μm for each device, which is in good agreement with the expected energy, E_{01}, for the $0\rightarrow1$ intersubband excitation in the QW.

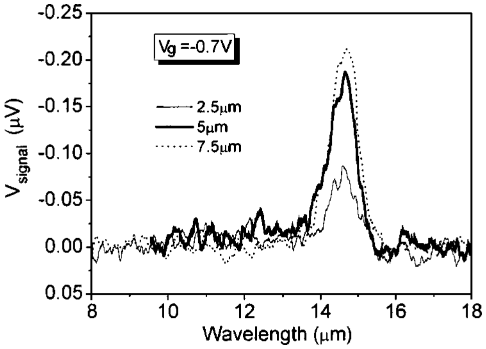

FIG. 4. Excitation spectrum in devices with $g=2.5$ μm, 5 μm, and 7.5 μm.

The fact that the peak position is substantially unaffected by the grating period suggests that the grating-induced resonance structure is insignificant, compared to the sharp energy levels in the QW.

We have also fabricated devices without metal grating. Though not shown here, additional experiments confirmed that those devices yield no discernible photoresponse. This fact, together with all the other findings described above, provide definite evidence that the bound-to-bound $(0 \rightarrow 1)$ intersubband excitation in the isolated QW island leads to a positive charge up of the island and its influence on the conductance of the remote 2DEG layer is sensed.

The intensity of relevant IR radiation ($\lambda = 14.8 \pm 0.5$ μm) emitted from the globar and reaching the active area (50×200 μm^2) of the device is roughly estimated to be on the order of 3 pW. The induced photosignal is about $V_{\rm sig} = -0.15$ μV (Figs. 3 and 4), or the induced relative change in conductance is about $\Delta G/G = +0.001\%$. Noting the signal to noise ratio, we roughly estimate the detectivity to be on the order of $D^* = 1 \times 10^9$ cm Hz$^{1/2}$/W. As discussed below, we suppose that this apparent detectivity is significantly suppressed by a saturation effect of the coexisting 300 K-black-body radiation and that the intrinsic detectivity can be much higher.

We find in the inset of Fig. 3 that at $V_g = -0.59$ V the conductance increases step wise with decreasing $V_{\rm g}$ as large as $\Delta G/G = +7\%$. This jump of conductance is independent of globar radiation, but disappears if we block all radiation by housing the device within a 4.2 K-metal can as shown by the dashed curve in the inset. Thus, this conductance change is ascribed to the influence of 300 K-black-body radiation ($\lambda = 14.8 \pm 0.5$ μm). We also notice in Fig. 3 that a significant fluctuation of resistance takes place when the QW island is isolated ($V_g < -0.59$ V). The fluctuation shows up also when the globar is turned off, as shown by open dots in Fig. 3. (Though not shown here, the fluctuation is absent when the device is placed in the completely dark condition.) These findings make it highly probable that the isolated QW island charges up significantly via $0 \rightarrow 1$ intersubband excitation due to 300 K-black-body radiation, and that the number of excited holes on the isolated QW island statistically fluctuates. Considering the optical scheme, we roughly estimate the power of 300 K-radiation reaching the device in the relevant wavelength region ($\lambda = 14.8 \pm 0.5$ μm) to be on the order of 70 pW. We note that the amplitude of the 300 K-radiation-induced ΔG (7%) is larger than that of the globar-induced ΔG (0.001%) by a factor as large as 10^4, whereas the radiation intensity of the former is larger than that of the latter only by a factor of 23.

In general, the response to radiation, ΔG, increases linearly with the radiation intensity P only if the radiation is so weak that the electrostatic potential in the heterostructure does not change its profile. The response ΔG will level off as the electrostatic potential of the QW island decreases substantially, and is completely saturated when the amplitude of decrease, ΔU, approaches the excitation energy E_{01}. In our detector, the ground-state subband of the QW island should line up with the Fermi level of the 2DEG channel in the dark. When exposed to IR radiation, the QW island is positively charged up decreasing its electrostatic potential. As the potential decreases, the responsivity, $\Delta G/P$, decreases because the recombination lifetime of photoexcited electron/hole pairs decreases. Furthermore, part of photoexcited electrons can possibly be trapped within the graded barrier without reaching the 2DEG layer, screening the effect of the positive charge in the QW island. The experimentally found increment of conductance $\Delta G/G = 7\%$ in the presence of background radiation makes us to expect that the ground state subband of the QW island is lower than the Fermi level by about $\Delta U = e^2 \Delta n_2 / C_{12} \approx 60$ meV, where C_{12} is the capacitance between the QW island and the 2DEG channel, and $\Delta n_2 \approx (\Delta G/G) n_2 = 1.5 \times 10^{10}$ cm^2 is the electron density increase in the 2DEG channel. Since the amplitude of ΔU is comparable to $E_{01} \approx 90$ meV, we expect that our detector is saturated due to the background black-body radiation,[11] and interpret the relatively low value, $D^* = 1 \times 10^9$ cm Hz$^{1/2}$/W, to be a consequence of strong saturation. The intrinsic detectivity, $(\partial G/\partial P)_{P=0}$, may be much higher than $D^* = (1 \times 10^9) \times (7\%/0.001\%) \times (1/23) = 3 \times 10^{11}$ cm Hz$^{1/2}$/W.

In summary, we have demonstrated a scheme of infrared photodetection. Incident light induces intersubband transition in an isolated QW island and causes the island to charge up. This changes the electrostatic potential of a remote 2DEG conducting channel through capacitive coupling, and causes its conductance to increase.

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[11] This expectation is supported by the additional experimental finding that the amplitude of photosignal increases when another black polyethylene film of 4.2 K is added: The signal does increase despite the total radiation intensity is reduced to about 15%!