Very low noise photodetector based on the single electron transistor

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We demonstrate the use of the single electron transistor (SET) as an amplifier for a photodetector operated at 20 mK. The unparalleled low input noise of the SET permits the observation of very small numbers of charge carriers generated in a bulk p-type Si substrate. We present data showing the response of the detector when it is illuminated by extremely low levels of red light ($\lambda=650$ nm). From the "dark current" noise of 0.06 e/s, we estimate a dc noise-equivalent power NEP$=2\times10^{-21}$ W/$\sqrt{\text{Hz}}$ for infrared light with $\lambda=30$ μm, and from this calculate a detectivity $D^*=8\times10^{17}$ cm$\cdot\sqrt{\text{Hz}/\text{W}}$.

The development of the planar-junction single-electron transistor (SET) by Fulton and Dolan[1] based on the ideas of Averin and Likharev,[2] has given experimentalists a device which can measure subelectron changes in the charge coupled to the SET input gate. This new device has been used to measure the presence of single electrons in circuits consisting of small capacitors and tunnel junctions,[3,4] giving a clear demonstration of single-electron charging effects. The extremely low noise of the SET, which corresponds to a measured charge fluctuation on the input gate of less than 1.5×10^{-4} $e/\sqrt{\text{Hz}}$ between 2 and 200 Hz,[5] permits such measurements to be made easily at temperatures $T<100$ mK. In this letter we describe the use of the SET as a detector of free-charge carriers generated in a bulk semiconductor by very low levels of light.

In Fig. 1 we show the equivalent circuit diagram of the experiment, where the SET consists of two ultrasmall planar tunnel junctions connected in series. The central lead between the two junctions is coupled to a bias lead through a gate capacitor C_g, and to a long metal finger through C_c. The operation of the SET is based on the Coulomb blockade of charge,[2] which occurs when the total capacitance C of the central lead satisfies $e^2/2C \gg k_BT$. The central lead capacitance is given by $C\cong C_1+C_2+C_c+C_g$, and is dominated by the capacitances $C_{1,2}$ of the two tunnel junctions. These junctions are fabricated by scanning electron microscope (SEM) lithography,[6] and typically have capacitances $C_{1,2}\ll1$ fF; the Coulomb blockade will then be observed only when the SET is operated well below $T=1$ K. The extremely high sensitivity of the SET is due to the fact that the current I passing through the two tunnel junctions is strongly modulated by the charge on the capacitors C_c and C_g, with a period e;[1,2] small changes in this charge then induce measurable changes in the current.

In the experiment described here, the long metal finger connected to the SET through C_c was intended to detect charges generated in the Si substrate upon which the device was fabricated. This finger was placed between two metal leads which act as charge collection plates (Fig. 1). The plate nearest to the finger was biased with a dc voltage V_c to generate an electric field between it and the further plate; this field would attract or repel free charges generated in the Si substrate between the two plates. A voltage of 0.1 V applied to this plate would create a field of about 10^2 V/cm in the Si. Charges collected near the finger would induce a screening charge in the finger, changing the charge on the capacitor C_c, in turn modulating the current I through the SET. The bias gate capacitor C_g was used to select the bias point of the transistor, and was used to maintain that bias point when the SET was operated in a feedback loop.

The entire device was fabricated on an oxidized p-type Si chip with a room-temperature resistivity of 6 Ω cm, corresponding to a boron doping density of $2\times10^{15}/\text{cm}^3$. The oxide layer was 450 nm thick, and no electrical contacts were made to the Si substrate: We relied upon the capacitive coupling of the charge carriers to the metallic finger to give rise to the signal. The finger had a total calculated capacitance $C_f=1.8$ fF, and the coupling capacitor to the SET was calculated to be $C_c=0.15$ fF.[7] An electron in the Si placed directly under the finger would therefore induce a charge somewhat less than $\Delta q=(C_c/C_f)e=0.083e$ on C_c.

The device was fabricated using a standard trilayer resist patterned by SEM lithography, onto which we evaporated two layers of AlSi alloy (1% Si) at two different angles, with an oxidation step between the two evaporations. The device was mounted on the mixing chamber of a dilution refrigerator, and was illuminated by a 1 mm diam

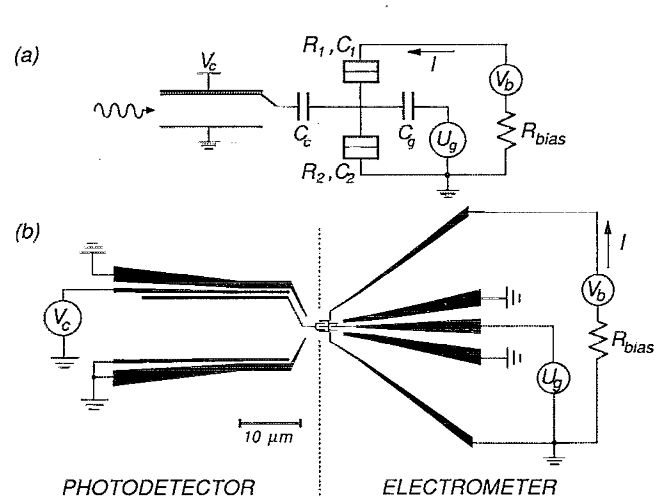

FIG. 1. (a) Circuit diagram for the experiment. The tunnel junctions had resistances $R_{1,2}\cong330$ kΩ and capacitances $C_{1,2}\cong0.5$ fF; the gate capacitor $C_g=0.098$ fF, and the finger capacitor $C_c=0.15$ fF. (b) Geometrical layout of the metallic parts of detector, deposited on the photon-absorbing Si substrate.

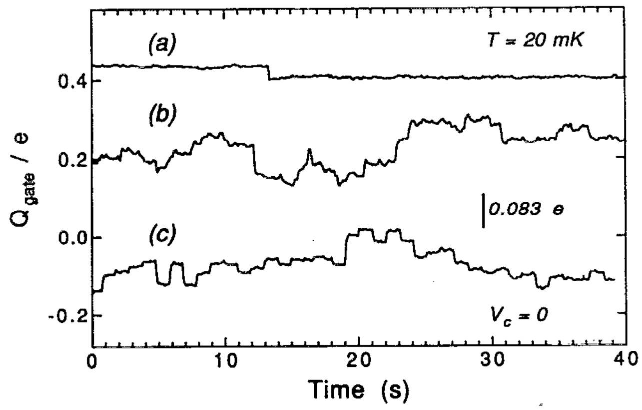

FIG. 2. Detector response under three illumination conditions, with the SET operated in feedback mode to maintain the bias point: (a) No light incident on the detector, the jump is an example of the "dark current" signal. (b) Continuous illumination, with a power absorbed in the detector of approximately 5×10^{-17} W. (c) Pulsed illumination, with 80 ms long pulses repeated every 1 s, with the same peak power as in (b). No bias voltage was applied to V_c for these data, and the vertical marker indicates $\Delta q=0.083$ e.

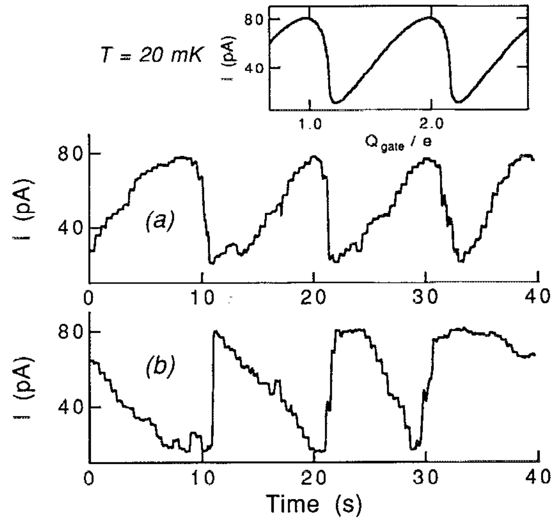

FIG. 3. Demonstration that the light-induced charge under the finger accumulates in the direction corresponding to the applied collector voltage, under pulsed illumination conditions with 50 ms long pulses at 2 s^{-1}, with peak power as in Fig. 2(b). Inset: Response of SET current to variations in the gate charge Q_{gate}. (a) SET response with a collector voltage of +0.65 V; the SET response corresponds to a decreasing charge in the substrate under the finger. (b) SET response with a voltage of −0.65 V; the response corresponds to an increase in the charge under the finger.

optical fiber which passed from room temperature, through an optical filter at 0.6 K, and illuminated the device from above at glancing incidence. The light source was a $\lambda=650$ nm GaAlAs LED, which was either used in continuous or pulsed operation. The red light from the LED was attenuated by 110 ± 4 dB upon reaching the detector, where the detector area of 300 μm^2 has been taken into account; the bandpass optical filter at 0.6 K attenuated light with $\lambda>750$ nm and $\lambda<600$ nm by an additional 60 dB.

In Fig. 2 we show the response of the SET under various illumination conditions, with no bias voltage applied to V_c. The bias point of the SET was fixed by operating the device in feedback mode and monitoring the feedback voltage applied to the gate capacitor C_g; this voltage was calibrated in units of electrons on C_g. The signal consists of jumps of various sizes, which can be compared to the value Δq for an electron placed on C_f. In the case of continuous illumination the jumps appear at random intervals, with varying sizes, and in the pulsed case the jumps occur during the pulses; some pulses did not induce an event, while most induced jumps of roughly the same size; these pulse-induced jumps are smaller than but of the order of Δq. The observed jumps correspond to both increases and decreases in the charge on C_c, as the bias voltage $V_c=0$ V does not impose a direction for charge collection. If the device was not illuminated, very few jumps were seen; the measured "dark current" was a jump rate of 0.06 ± 0.02 s^{-1}.

We believe these signals are caused by the motion of charge carriers, excited into the conduction or valence band, where they can travel through the Si until they are retrapped. The most likely excitation process is photon-stimulated electron-hole generation, which gives a 5 μm penetration depth for $\lambda=650$ nm light in Si at low temperatures.[8] The change in the charge distribution near the finger induces a screening charge measured by the SET, and the varying sizes in the jumps would be due to variations in the distances traveled by the charge carriers before they are trapped. The fact that the typical sizes of the jumps are of order Δq supports this hypothesis. This detector should, in principle, be able to detect single photons with energies down to the smallest donor energies in Si, which is about 45 meV (or $\lambda\leqslant30$ μm); this could perhaps be extended to $\lambda\approx300$ μm by using very shallow donors.[9]

In Fig. 3 we show that the sign of the charge accumulated under the finger is consistent with the sign of the voltage V_c applied to the collector plate. In the inset to the figure we display the dependence of the SET current on the gate charge $Q_g=C_gU_g$. The bias resistor R_{bias} for the SET was large enough to make this curve asymmetric, which allow us to measure the sign of the change in the charge trapped near the finger. In Figs. 3(a) and 3(b), we show that a voltage of $V_c=+0.65$ V causes the charge in the Si to decrease and a voltage of $V_c=-0.65$ V causes it to increase, as expected. This sensitivity to V_c also indicates that the effects seen are not due to an indirect heating of the substrate or the SET, caused by the illumination.

In Fig. 4 we display the dependence of the jump rate on the light pulse duty cycle and repetition rate, as well as on the intensity of the light in continuous illumination. The jump rates were extracted from the data by counting the rate at which the charge on C_c jumped by more than 0.02 e for a typical digitization step of 0.04 s, i.e., more than 0.5 e/s. The jump rate is found to depend linearly on all three parameters, as expected.

The device was found to gradually saturate after about 10^4 jumps for voltages $V_c\approx1$ V applied to the collector plate. We believe that the charge carriers in the Si gradually screen the applied field, as a charge of about 10^4 e would correspond to the charge on the plate in the prox-

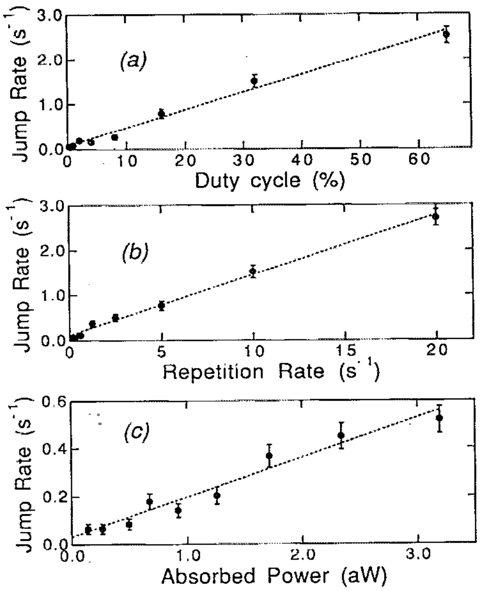

FIG. 4. Response of the detector when under: (a) Pulsed illumination with 5 s^{-1} repetition rate, varying the duty cycle, (b) 6 ms pulses, varying the repetition rate, (c) continuous illumination, varying the light intensity. The light intensity in (c) is uncertain by about a factor of two. The pulse power in (a) and (b) is as for Fig. 2.

imity of the finger. Changing V_c to $-V_c$ caused jumps in the direction corresponding to the systematic discharge of the Si, which again saturated after roughly the correct amount of charge was transferred. These problems of saturation could be eliminated by making ohmic contacts to the Si and thereby removing the charge carriers.

In conclusion, we have demonstrated the operation of a photodetector using a charge amplifier with an intrinsic noise of far less than one electron per unit bandwidth. If we assume an ideal detector with a collection efficiency of $\eta=1$, the dark current corresponds to a minimum light flux of $\Gamma=0.06$ photons/s. For infrared light with $\lambda=30$ μm, the calculated noise-equivalent power would be NEP $=(hc/\lambda)(2\Gamma)^{1/2}=2\times10^{-21}$ W/$\sqrt{\text{Hz}}$, and the corresponding detectivity for this detector with area $A=300$ μm^2 would be $D^*=\sqrt{A}/\text{NEP}=8\times10^{17}$ cm$\cdot\sqrt{\text{Hz}}$/W. Note that we would not achieve an efficiency $\eta=1$ with the geometry used here, as the penetration depth is about 500 μm for light with $\lambda=30$ μm,[10] so few of the excited carriers would be collected. The extremely low noise of the SET should nonetheless allow us to detect single charge carriers in the substrate, and a more effective collection geometry should allow us to make a clear demonstration of single-photon detection at infrared frequencies.

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