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An Extremely Low Noise Photodetector Based on the Single Electron Transistor

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We have demonstrated 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 detection 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). Although we are not able to prove that individual charge carriers are being detected in our system, the magnitude of the detector response and the level of noise in the system are in good agreement with single charge, and therefore single photon, detection. From the "dark current" noise of 0.06 electron/s, we estimate a noise-equivalent power NEP = 2×10^{-21} W/$\sqrt{Hz}$ for infrared light with $\lambda = 30$ μm, and from this calculate a detectivity $D^* = 8\times10^{17}$ cm-$\sqrt{Hz}$/W.

Over the past few years experimentalists have developed a number of novel devices which can control and detect single electrons in an electrical circuit. These devices are based on the Coulomb blockade of charge[1], in which electrons are prevented from entering a small piece of metal simply because the energy to charge that piece of metal with a single electron is much larger than the available thermal energy. One of the first successful devices to be based on this effect was the single electron transistor (SET), developed by Fulton and Dolan[2]. This new device is unique in its ability to detect a charge of far less than one electron: The noise for charge coupled to its input gate has been measured[3] to be less than 1.5×10^{-4} e/$\sqrt{\text{Hz}}$ for frequencies between 2 and 200 Hz. This 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 SET has furthermore been shown to exhibit voltage gain[5]. In the following paper we show how we used the SET as the first stage amplifier for a Si photodetector for visible red light, and discuss how this device might be used for the detection of single infrared photons.

The single electron transistor in our implementation consists of two 0.1×0.1 μm^2 planar tunnel junctions connected in series, as shown in the schematic in Fig. 1. The SET is operated by applying a DC voltage across the junctions and monitoring the resulting current. The Coulomb blockade of charge controls the behavior of the device for temperatures T such that $k_BT < e^2/2C$, where C is the total capacitance of the central lead between the two junctions. The current is then strongly affected by the charge coupled to the central lead; this charge is coupled to the SET either through the bias gate capacitor C_g or through the signal capacitor C_c. The current is modulated by the charge on these capacitors with period e, and very small changes in this charge can induce a measurable change in the current. Note that the limit on the temperature T places a limit on the central lead capacitance $C \cong C_1 + C_2 + C_c + C_g$, which is dominated by the junction capacitances $C_{1,2}$; the SET is fabricated using scanning electron microscope lithography, which allows us to fabricate junctions with capacitances $C_{1,2} \leq 1$ fF. If the two coupling capacitors are kept below this value, the device will operate for temperatures $T \leq 300$ mK.

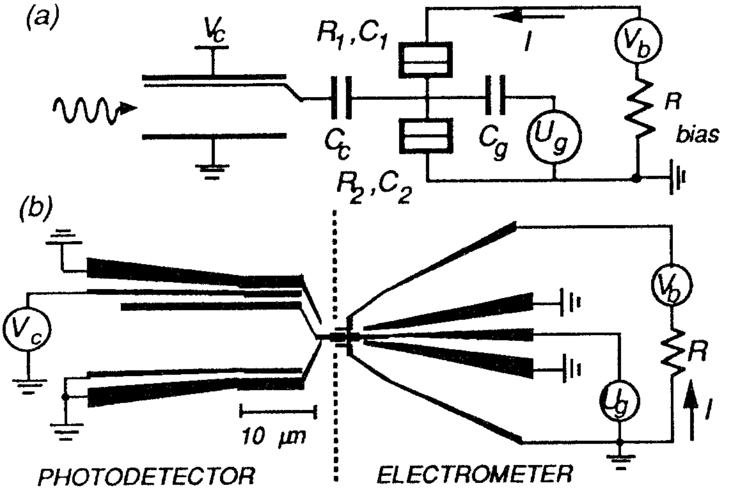

Fig. 1. (a) Electrical circuit for the experiment. The tunnel junction resistances were $R_{1,2} \cong 330$ kΩ and capacitances $C_{1,2} \cong 0.5$ fF; the gate capacitor C_g = 0.098 fF, and the long finger capacitor C_c = 0.15 fF. (b) Geometrical layout of the metallic parts of detector, deposited on the photon-absorbing Si substrate.

The long metal finger connected to the SET through C_c was used to detect charges generated in the Si substrate upon which the device was fabricated. This finger was placed between the 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 other plate; this field attracts or repels free charges generated in the Si substrate. Charges collected under the plate nearest the finger induce a screening charge in the finger, changing the charge on the capacitor C_c, which in turn modulates the current I through the SET. The gate capacitor C_g was used to change the bias point of the SET, and could be used to maintain the optimal bias point when the SET was operated in feedback.

The entire device was fabricated on an oxidized p-type Si wafer with a room-temperature resistivity of 6 Ω-cm, due to a boron doping density of $2 \times 10^{15}/\text{cm}^3$. The wafer had a 450 nm thick oxide layer, and no electrical contacts were made to the Si substrate: The charge carriers generated in the Si coupled capacitively to the long metal finger, which in turn was capacitively coupled to the SET. The finger had a total capacitance C_f = 1.8 fF, and the coupling capacitor to the SET was calculated[7] to be C_c = 0.15 fF. An electron trapped in the Si directly under the finger would therefore induce a charge on C_c somewhat less than $\Delta q = (C_c/C_f)\, e = 0.083\, e$.

The device was mounted on the mixing chamber of a dilution refrigerator, and was illuminated by a 1 mm-diameter optical fiber which passed from room temperature, through an optical filter at 0.6 K, and illuminated the device from above. The light source was a $\lambda = 650$ nm GaAlAs LED, and the 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 background light with $\lambda > 750$ nm and $\lambda < 600$ nm by an additional 60 dB.

In Fig. 2 we show the response of the SET with no voltage applied to the collection plates, under various conditions of illumination. 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 response of the device consists of jumps of various sizes, which can be compared to the value Δq for an electron placed on C_f. In Fig. 2(a) we show the response with no light incident; that figure shows a single jump in the charge coupled to C_c, and in general very few jumps were seen with no illumination. The measured "dark current" was a jump rate of $0.06 \pm 0.02\ s^{-1}$. In the case of continuous illumination, in Fig. 2(b), the charge jumps at random intervals, by varying amounts. In the case of pulsed illumination in Fig. 2(c), the jumps occur during the light pulses; some pulses did not induce an event, while most induced jumps of roughly the same size; these pulse-induced jumps were smaller than but of the order of Δq. The observed jumps in all cases 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.

These signals can be understood by considering the motion of individual charge carriers in the Si substrate. A charge carrier absorbs a photon and is excited into the conduction or valence band of the Si. The carrier then moves in the Si due to local electric fields, until it is retrapped; the charge carriers' motion induces a change in the charge coupled to the SET, and is detected as a jump in the SET bias point. The varying sizes in the jumps is due to variations in the distances travelled by the charge carriers before they are trapped. The fact that the typical sizes of the jumps are less than but of order Δq supports this hypothesis. The ability of the SET to detect single carriers means that this detector should be able to detect single photons with energies down to the smallest donor energies in Si, which is about 45 meV (or $\lambda \leq 30\ \mu m$); this could perhaps be extended to $\lambda \approx 300\ \mu m$.

In Fig. 3 we show the response of the detector when a voltage V_c is applied to the collector plates. In Fig. 3(a) is the response to a voltage $V_c = +0.65$V, and in Fig. 3(b)$V_c = -0.65$V. The unusual behavior can be understood by examining the inset to the figure, which shows the dependence of the SET current on the gate charge $Q_g = C_g U_g$; the asymmetric response is due to the use of a large resistor R_{bias} in the SET bias circuit, and the asymmetry allows one to distinguish increases from decreases in the coupled charge. This inset clearly shows that in Fig. 3(a) the charge under the collection finger is decreasing, while in (b) it is increasing, as one would expect. This figure also confirms that the jumps seen in the SET bias point are due to charge motion in the Si and not elsewhere in the circuit, as otherwise the response would not depend on V_c.

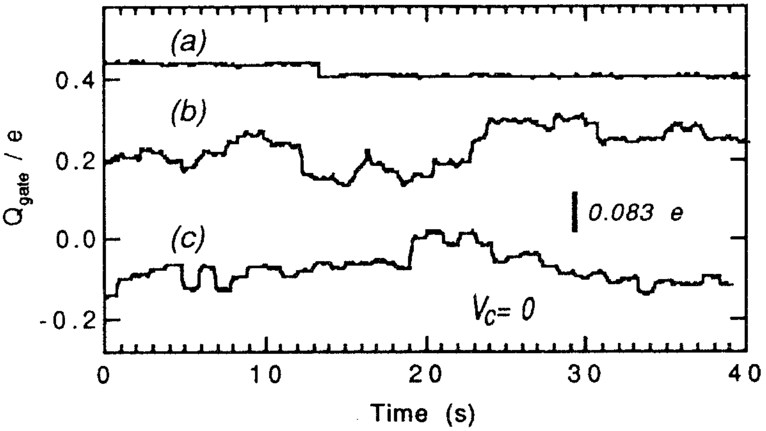

Fig. 2. Detector response under three illumination conditions: (a) No incident light; the jump is an example of the "dark current" signal. (b) Continuous illumination, with a power of approximately 5×10^{-17} W. (c) Pulsed illumination, with 80 ms-long pulses every 1 s, with peak power as in (b). No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

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. From Fig. 4(c) we expect to see 1 jump/sec for an incident power of 5.2 aW, or about 17 photons/sec. If we are indeed observing single charge carriers, then our collection efficiency is about η = 0.06, which is rather poor compared to standard photodetectors, but is probably due to the crude collection geometry. From this figure we can estimate the noise-equivalent power for this device, which for a dark current of $\Gamma = 0.06\ \mathrm{s}^{-1}$ is $NEP = (hc/\lambda)\ (2\Gamma/\eta)^{1/2} = 4.3 \times 10^{-19}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$.

The response of the device was found to disappear after about 10^4 jumps for voltages $V_c \approx 1$ V applied to the collector plate. We believe that after 10^4 jumps the charge carriers photogenerated in the Si have completely screened the applied field, as a charge of about 10^4 e would correspond to the charge on the plate in the proximity of the finger. Changing V_c to $-V_c$ caused the device to respond again, but with jumps in the opposite 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.

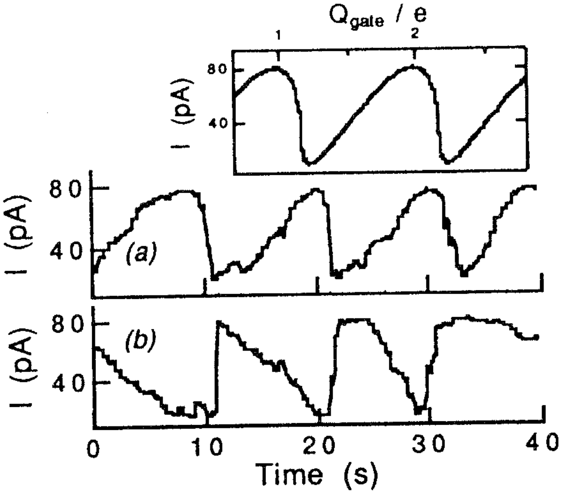

Fig. 3. Response of the device to light when a collector voltage V_C is applied. (a) SET response with a collector voltage of +0.65 V. (b) SET response with a voltage of −0.65 V. Inset to the figure: Response of SET current to variations in the externally applied gate bias charge Q_{gate}. The illumination in (a) and (b) was pulsed with 50 ms long pulses at 2 s^{-1}, with peak power as in Fig. 2(b).

In conclusion, we have demonstrated the operation of a photodetector using a SET 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 $NEP = 2\times10^{-21}$ W/$\sqrt{\text{Hz}}$, and the corresponding detectivity for this detector with area $A = 300$ µm^2 would be $D^* = \sqrt{A}/NEP = 8\times10^{17}$ cm-$\sqrt{\text{Hz}}$/W. Note that we could not achieve an efficiency $\eta = 1$ with the geometry used here, as the penetration depth for light with $\lambda = 30$ µm is about 500 µm[8], 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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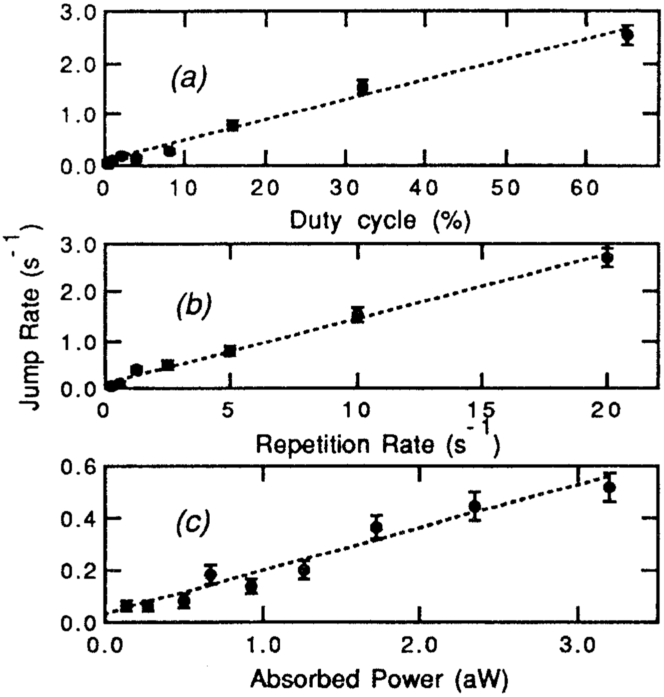

Fig. 4 Response of the detector under different illumination conditions. (a) Pulsed illumination with 5 s^{-1} repetition rate, varying the duty cycle, (b) 6 ms pulses, varying the repetition rate, (c) continuous illumination, varying the light intensity. The light intensity in (c) is uncertain by about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

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