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Effects of Visible Light On Al/AlOx Single-Electron Transistors

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***Abstract*— We study the effects of visible light illumination on the behavior of Al/AlOx single-electron transistors (SETs) with different island size and geometry using semiconducting and insulating substrates at low temperatures (0.3 -4.2 K). Experimental data show several effects on the SET conductance caused by the light illumination.**

I. INTRODUCTION

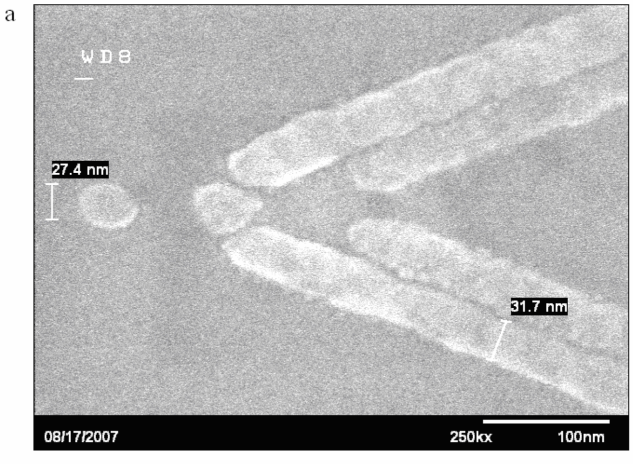
Single Electron Transistors (SETs) are charge sensitive devices which can be used as electrometers to detect charge changes, with demonstrated sensitivities of down to 1×10^{-6} e/$\sqrt{\text{Hz}}$ at 8 MHz for RF-SET [1]. SETs are indispensable tools in measurements requiring sub-electron charge sensitivity including single-electron memory and logic [2]. The unprecedented sensitivity of the SETs makes them the sensor of choice for large number of applications where a change in distribution of charge in nanostructures must be measured. Currently, we are investigating the so–called "blinking" phenomenon exhibited by semiconductor dots and nanowires [3]. This blinking phenomenon consists of both random periods of photoluminescence and random periods where no light is emitted, despite the continuous light excitation of the nanoscale structures. By understanding and controlling this blinking phenomenon, photoluminescent molecules could be used for imaging and monitoring dynamic processes in biological systems. The process of "blinking" is believed to be associated with charge redistribution within the structures, hence, SETs are excellent candidates to detect these charge changes. By placing the nanoscale molecules near the island of the SET, and continuously irradiating them using a Near-field Scanning Optical Microscope (NSOM), modulation of conductance of the SET is expected to be correlated with charge redistribution within the molecule. To employ SETs in a measurement involving light effects it is necessary to understand their performance and behavior in the presence of light. For that reason, in this work we study the effects of light illumination on the behavior of the SETs fabricated with different device geometries and substrate materials.

II. FABRICATION & DEVICES

Typical Al/AlOx SETs fabricated using Dolan bridge technique [4] have charging energy less than 1 meV. However, the NSOM used for optical excitation and detection of blinking dots has a minimal operation temperature about 4K. Therefore the charging energy of the SETs used in the experiment must be significantly higher than 0.34 meV (thermal energy at 4K). Using high resolution e-beam lithography and carefully choosing evaporation angle and oxidation time we developed fabrication technique to consistently fabricate SETs with charging energies of ~3 meV.

Prior to the integration of SET with blinking objects the effect of visible light on SETs must be investigated as to date there is no reported investigation of SET behavior under direct visible light illumination. A number of devices are studied in this report, varied by island shape (from small disk-like "dots" to wide "cross-like" islands) and gate to island distances (0.2 to 2 μm from the island). The substrate materials used in this study are p^- Si substrates with total thickness of the wafers of 620 μm with thermally grown SiO_2 or insulating 500 μm thick quartz substrates.

Figures 1a-1c shows the SEM micrographs of the SETs with various island areas: (a) 7×10^2 nm^2; (b) $1.35\times10^5 nm^2$ and (c) $3\times10^5 nm^2$.



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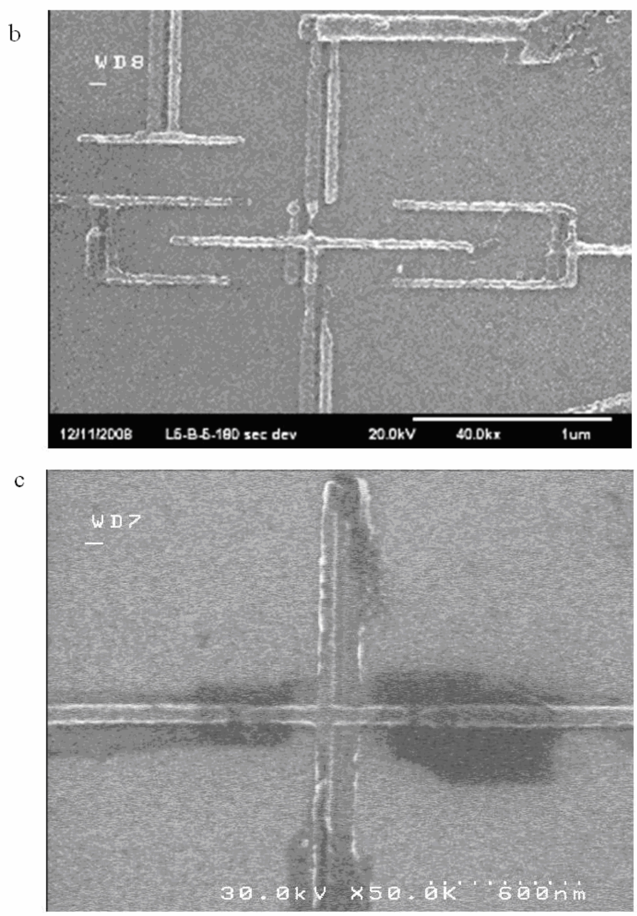
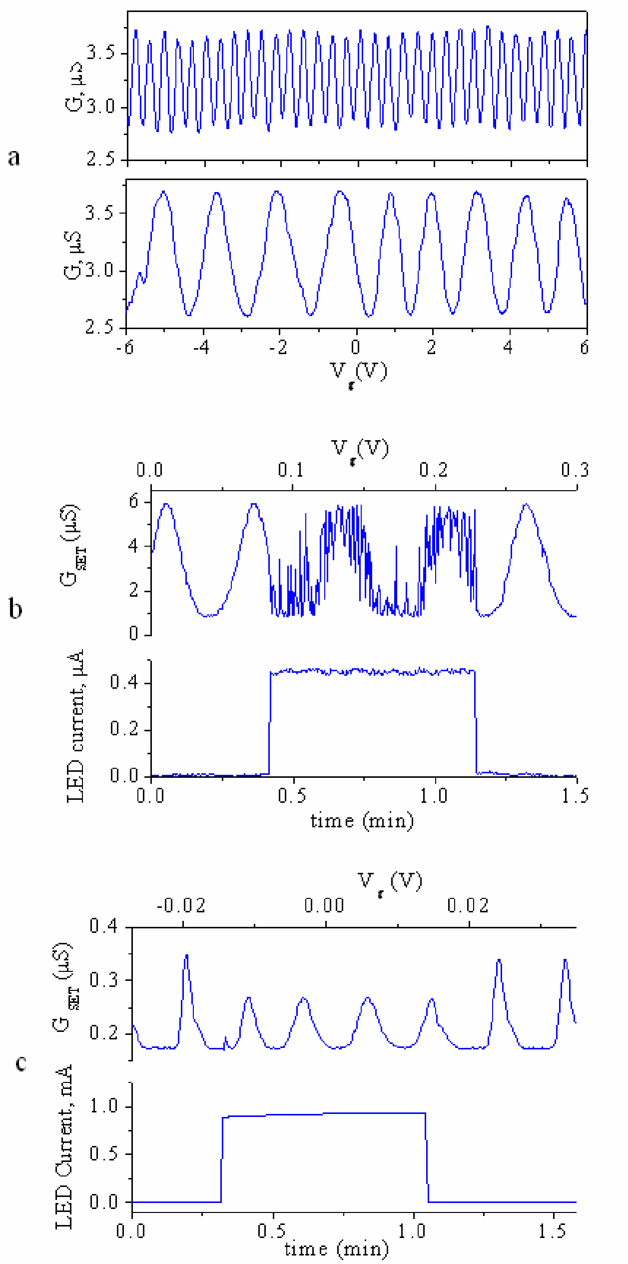


Fig. 1 SEM micrograph of the SETs with various island areas: (a) 7x10^2 nm^2; (b) 1.35x10^{5}nm^2 and (c) 3x10^{5}nm^2.

III. EXPERIMENTAL RESULTS

A variety of experiments are performed using continuous and pulsed visible light illumination on SETs; at a temperature range of 0.3-4.2K. For the experiments using continuous light illumination, the conductance of the SETs is monitored while the gate voltage is being scanned. Next, the conductance is studied for different light intensities and compared with the ones taken in darkness. Low temperature conductance measurements are performed using standard lock-in techniques with AC excitation signal 0.1-1 mV at frequencies in the range 10-3000 Hz. The light sources used in the experiments consist of visible light LEDs coupled to optical fibers routed to the sample. The beam diameter of 1 mm ensures every device is illuminated when the source is on. Assuming a 100% efficiency for the LED and no losses in the optical fiber, a beam diameter of 1 mm, and a current of 1 mA flowing through the LED, we estimate an upper limit for the incoming photon flux of 8000 photons/sec·nm^2. Next we notice that the reflection of Al in the visible light range is close to 93 % [5]. With this estimate and the fact that the SETs' island is very small in area (<3 x10^5 nm^2), the current produced by photoexcited electrons would be too small to be detected, (<30 pA). Moreover, this extra component of current is a DC current whereas the measurements are done using small signal AC metrics. Therefore, we neglect any direct photo current generated by the photons absorbed on the island of the SET.

Experimental results show several effects on the SET conductance caused by the light illumination: the change in the period of the Coulomb blockade oscillations (CBOs) (Fig. 2a); a drastic increase of the electrical noise (Fig. 2b); reduction of the amplitude of (CBO) peaks in the presence of light (Fig. 2c); smearing, or washing away, of the CBOs (Fig. 2d).



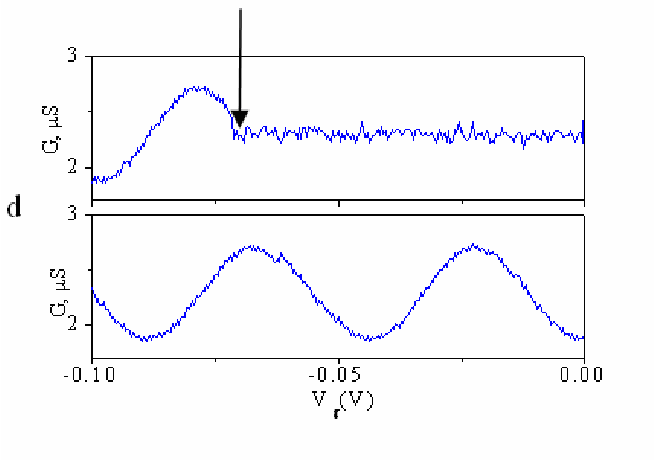


Fig. 2 Response of the SET conductance to red LED illumination (a) Change in the period of oscillations. Top curve is measured at LED current=200 µA, bottom curve is measured in the dark; T=4.2K (b) Noise appearance as small photon flux (LED current=0.5 µA) is applied. Bottom curve shows current pulse, in time, applied to the LED; T=0.3K (c) Light induced peak lowering at higher light intensity (LED current=1 µA) ; T=0.3K (d) Smearing of the CBOs for larger size SETs LED current=40 µA, arrow point to the instance when light is applied; T=0.3K.

The first effect is distinctly different from the last three because the magnitude of the CBOs stays the same, but the period is changing. For that reason we will refer to it as frequency modulation (FM) effect. For the last three of observed effects the amplitude of the CBOs is affected, while period is unchanged, therefore we will call these amplitude modulation (AM) effects.

Let us first consider the FM effect. This effect reveals itself only for the smallest, “dot-like” devices (Fig 1a) which have the highest gate to island separation (2 µm) and fabricated on SiO_2/Si substrates. By comparison , devices fabricated on quartz substrates with exactly the same gate and island configuration (Fig. 1a) show no FM effect (Fig. 3)

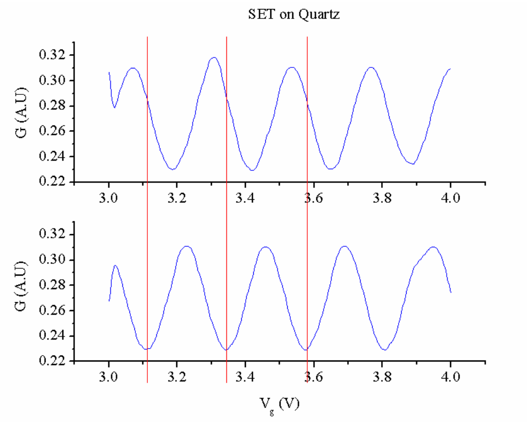


Fig. 3 SET fabricated on quartz substrate shows no response to light illumination.

This leads us to the conclusion that the presence of semiconducting substrate plays a crucial rule in observation of the FM effect.

Indeed, the period of the CBO is given by $\Delta V_g = e/C_g$, where C_g is the capacitance between the SET and the gate. Therefore, the FM effect (change in the CBO period) must correspond to a change in the gate capacitance. The absorption of a photon with energy above the bandgap, E_g, in the Si substrate creates an electron-hole pair (EHP) which then can be swept towards electrodes to which a voltage is applied (gate electrode, source-drain wires). The generated carriers (that come either from interband carrier generation or interface states at Si/SiO_2 interface) promote photoconductance in the Si substrate which increases the coupling between the SET and the gate and thus leads to a smaller period of CBOs. To qualitatively estimate this change let us consider the case when semiconducting substrate is replaced with a floating metal substrate. Using a parallel plate capacitor model (with the same dielectric) we arrive at CBO period of about 0.2 V which is about 2 times smaller than observed value of ~0.4 V under light illumination. This in turn means that this crude “metal substrate” model overestimates the increase of capacitance.

Figure 4 shows a more realistic circuit model that explains observation of FM effect by increased gate coupling caused by Si substrate photoconductivity. This photoconductivity was measured directly and results will be reported elsewhere [6]. In case when truly insulating wide bandgap substrates were used (0.5 mm thick crystalline quartz) no FM effect is observed as there is no light absorption in such substrates (G(L.I.)=0).

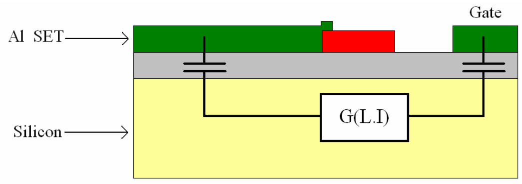


Fig. 4 Circuit schematic of the charge excitation in the Si substrate, responsible for change in the periods of the CBOs. G(L.I) is light induced photoconductivity

Now, let us discuss the “AM effects”. Figure 2b shows a drastic increase of the electrical noise in larger structures (fig 1 b and 1c) for low intensities of light. This light induced noise is followed by either peak lowering with simultaneous reduction of the peak amplitude (for “medium” sized devices, Fig. 1b) or by complete smearing of oscillations (largest sized devices, fig. 1c). Taking into account the fact that AM effects, in particularly the light induced noise are insignificant for the smallest size devices, we suggest that the excitation-relaxation processes in the charged traps located in the close proximity to an SET island are responsible for the AM effects. First, the increase of noise at very low light intensities (100nA) can be induced by several individual traps (“single-photon detection regime”) in a way it was reported in [7]. In this case, the effective cross-section of the detector increases as the size of the island increases. We are currently investigating whether the *area* or the *perimeter* of the SET island plays a major role in the sensitivity increase. This will allow us to identify the location of the charged traps.

The reduction of the peak height (Fig 2c) in the SETs with medium sized islands can be explained by a simultaneous excitation-relaxation processes in many fast traps [6]. This fast charging of many traps produces "random modulation" signal in time domain which leads to the second light induced AM effect – reduction of the peak height. To verify this hypothesis we modulate the gate of the SET using a square signal with a frequency much higher than the lock-in test signal so that the resulting curve is a time average of the gate signal. Fig. 5 shows the reduction of the peaks on the CBOs caused by a square wave modulation which matches the peak lowering induced by the light.

Finally, for the SETs with the largest size island, the increase of electrical noise (similar to fig .2b) is followed by a rapid smearing of oscillations for the light intensity similar to that in fig 2d. The fact that the AM effect is the strongest in these devices is likely to be determined by two reasons: largest island size (which increases the number of coupled photon-excited traps and thus leads to a stronger random modulation) and it has lower charging energy and therefore much weaker gate modulation by V_g (~30%), leading to "sinusoidal" shape of CBOs (in which case random modulation can wash away the oscillations altogether). Thus, effects observed in Fig. 2c and 2d have the same origin, but different strength. The reason why the FM types of effects are not revealed in devices 1b and 1c is because by design the coupling to the gate is much stronger in these devices, so that extra coupling through a photoconducting substrate is less noticeable. To observe such FM effects in the devices with stronger coupling to the gate the range of gate bias scan has to be significantly extended so that the change in the number of CBO peaks within one scan becomes noticeable [6].

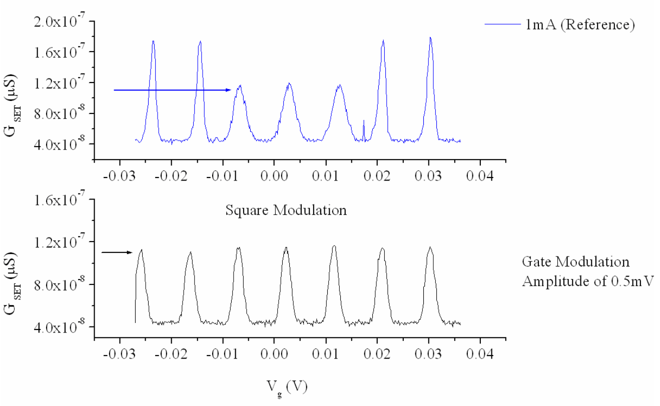


Fig. 5 Effects on the SETs conductance caused by modulation of the gate using a square signal from a function generator.

To summarize, we report a number of light induced effects in the conductance of the SET fabricated on insulating and semiconducting substrates with different island size and different coupling between the SET island and the gate. The observed effects can be separated into two major categories by the way they are related to the charge excitations promoted by absorbed photons. The first category of effects is attributed to "remote" charging events in the semiconductor substrate, when the SET responds to the remote "cloud" of charge in the substrate, rather than individual charging events. The second category of effects result from light induced excitations of the charge traps located in close proximity to the SET, which corresponds to photons absorbed in a close vicinity to the SET island (including the oxidized surface of the island) generating individual charging events which are revealed as "jumps" in the conductance of the SET.

To use SETs as charge detectors for blinking molecules, the effects of light on SETs should be alleviated to avoid detection of unrelated photon-excited effects. Our results also show that the SETs can also be used to implement highly sensitive photodetectors. We are currently investigating details of the possible mechanisms of charge interaction with light to optimize the performance of the SETs in a photon detector. The optimization and enhancement of the sensitivity of the SET photodetector involves control of the photon absorbing region of the device and its coupling to the SET electrometer for maximum sensitivity.

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