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Photo-Irradiation Effects in Single-Electron Tunnel Junction Arrays

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1. Introduction

Recently, single-electron tunneling (SET) devices have been extensively studied to develop mesoscopic electronic devices. In addition to electronic devices, application of SET to photonic devices is also attractive, because photon assisted tunneling [1,2] may lead to new devices such as photodetectors and photomemories with high spatial resolution. The purpose of this work is to study, for the first time, photo-irradiation effects on I-V characteristics and charge distributions in a voltage-biased tunnel junction array by a Monte Carlo SET simulation method [3] using a simple model considering tunnel-rate enhancement.

2. Calculation Model

We consider a voltage-biased array structure shown in Fig. 1 (a), where 20 ultrasmall tunnel junctions (therefore 21 nodes) are connected in series, and irradiate light onto a number of middle nodes. Parameter values of C, C_0 and R_d (tunnel resistance in the dark) used are 100 aF, 1 aF and 1 MΩ, respectively. Here, we modeled irradiation of light by reduced tunnel resistance R_{ph} (= 100 kΩ < R_d) for the irradiated area, as shown in Fig. 1 (b). This model is based on the fact that an electron excited by a photon (hν) feels lower tunnel resistance R_{ph} (higher tunnel rate) because effective tunnel barrier is lowered. In this model, it is assumed that (i) the number of excited electrons (excitation rate times lifetime) is kept constant in each irradiated node and (ii) when an excited electron tunnels to the dark node, the electron quickly releases the excess energy hν before successive tunneling occurs. Thus, the tunnel resistance is R_{ph} between irradiated nodes, while at the bright and the dark boundary the tunnel resistance is direction-dependent, i.e., R_{ph} from the bright to the dark node and R_d from the dark to the bright node.

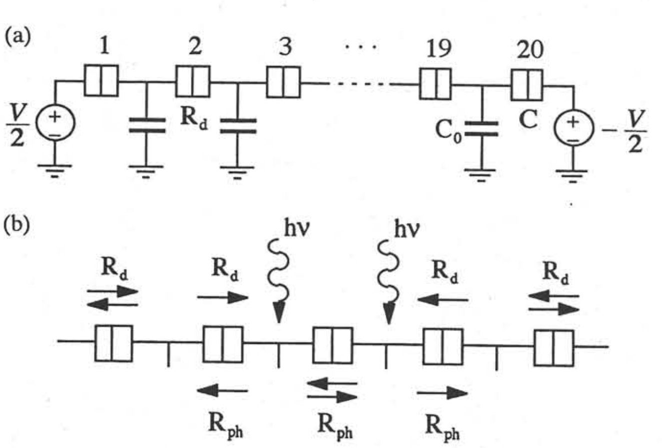

Fig. 1. (a) Equivalent circuit of the voltage-biased array structure. (b) Model of local irradiation of light.

3. Results

Photocurrent

We first simulated current-voltage characteristics of the array. The results are shown in Fig. 2, where the low voltage region is shown in the inset. The dark current is corresponding to Curve A, and the current under irradiation onto 5 middle nodes to Curve B and 11 middle nodes to Curve C. The Curve A is essentially the same as that reported by Likharev et al. [4]. The photo-induced current is obvious and increased with increasing number of irradiated nodes. The threshold voltage due to the Coulomb blockade effect, however, remains unchanged (11.4 mV). The circuit current at V = 500 mV as a function of the number of irradiated nodes is shown in Fig. 3. The photocurrent increases gradually and then quickly with increasing irradiation area. This result is interpreted as reduction of the total circuit resistance.

Charge Distribution

Steady state charge distribution (distribution of the number of electrons) in the array at V = 500 mV is shown in Fig. 4, where (a) and (b) show those in the dark and under irradiation (5 nodes irradiated), respectively. The negative number of electrons indicates positive charges produced by an outflow of electrons. The distribution in (a) fluctuates in space and in time [5], but long time-averaged charge is close to zero at any node. The distribution in (b) is interesting because negative

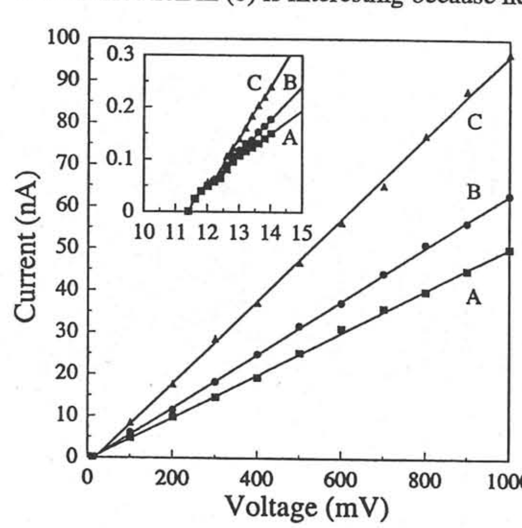

Fig. 2. Typical current-voltage curves of the array for 0 (a), 5 (b) and 11 (c) nodes irradiation, where the low voltage region is shown in the inset.

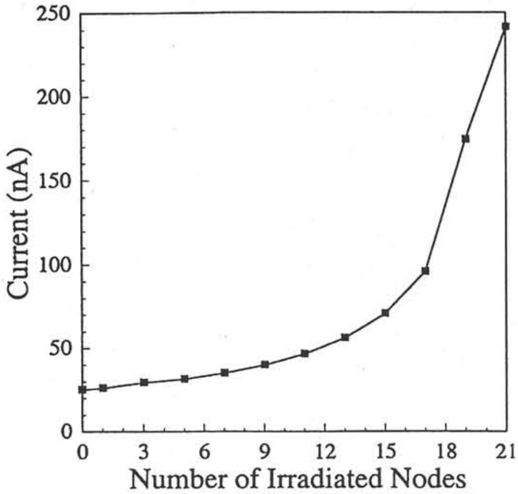

Fig. 3. Circuit current at V = 500 mV as a function of the number of irradiated nodes.

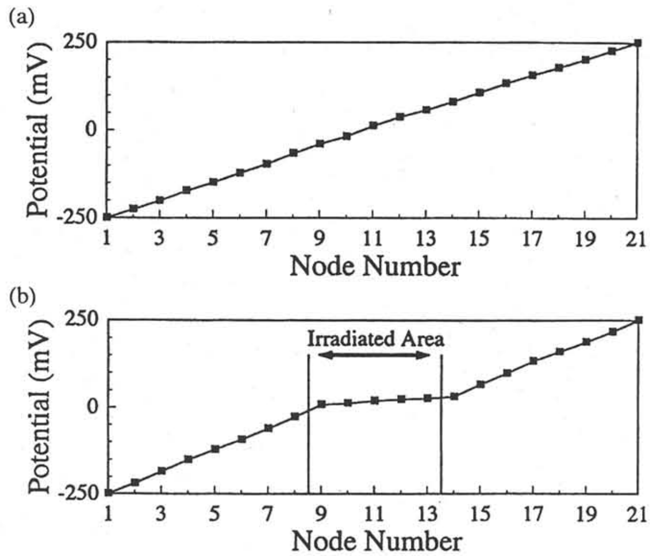

Fig. 5. Potential profiles corresponding to Fig. 4 (a) and (b).

and positive bumps are observed at the edges of the irradiated area. This asymmetric profile is caused by the asymmetric bias condition. Potential profiles corresponding to Fig. 4 (a) and (b) are shown in Fig. 5 (a) and (b). Photo-irradiation produces the flat potential in the irradiated area and screens the bias potential by the large charges at the both edges of the irradiated area.

Photomemory Effect

The results in Figs. 2 and 3 indicate applicability of a SET junction array to photodetectors. It is convinced that, as long as the array is not too long, excitation of only a few electrons leads to the large photocurrent. For practical application, the quantum efficiency of photon absorption in the volume of the nodes must be taken into account. The primary advantage in the use of a SET array may be high spatial resolution limited by the node size typically less than 100 nm. Another application is suggested by Figs. 4 and 5. If the dark tunnel resistance R_d is extremely large, the charge distribution like Fig. 4 (b) or the potential profile like Fig. 5 (b) will be sustained for a long period after the light is shut off. If we can detect the local potential profile by means of scanning probe microscopy or other techniques, this phenomenon can be applied to photomemory devices with ultra-high resolution.

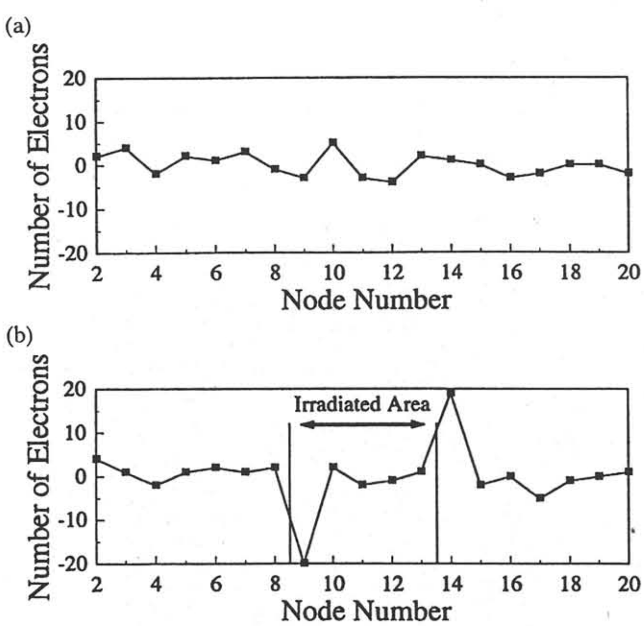

Fig. 4. Charge distributions at V = 500 mV (a) in the dark and (b) under irradiation.

4. Conclusions

Monte Carlo simulation of photo-irradiation effects in a SET junction array shows generation of photo-induced current. It is also found that under irradiation the characteristic charge distribution is formed resulting almost flat potential in the irradiated area. These results suggest the feasibility of photonic devices. Since the calculated model may be oversimplified, we should study further to construct a more precise model including the generation and recombination process.

References

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