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An Evidence for Ballistic Transport in Nanocrystalline Porous Silicon Layer by Time-of-Flight Measurements

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1. Introduction

Porous silicon (PS) consists of a large number of quantum-sized silicon nanocrystallites with the same band dispersions as single crystalline silicon (c-Si). As a strongly confined system, PS exhibits various useful photonic and electronic functions besides visible luminescence: nonlinear optical effect [1], nonvolatile memory [2], ballistic electron emission [3], and ultrasound generation [4].

Regarding the ballistic electron emission from PS diodes, the emission characteristics including the energy distribution of emitted electrons suggest that under a high electric field ballistic electrons are efficiently generated in the PS layer with a controlled structure. There is a possibility that electrons injected into the PS layer travel ballistically via multiple-tunneling through silicon nanocrystallites, and that kinetic energy gain of electrons reaches several to ten electron volts.

To confirm this hypothesis, the electron transport mechanism in the PS layer has been studied by a time-of-flight (TOF) measurement. Particular attention is paid upon whether or not the electron drift length is enhanced in the PS layer. An evidence for ballistic transport is presented here. Its technological significance is also discussed.

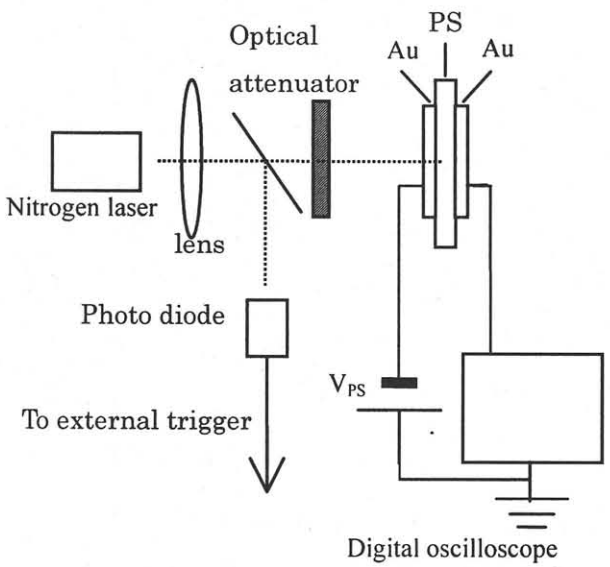

Fig. 1 Experimental setup for a TOF measurement. All measurements were done at room temperature.

2. Experimental Details

Experimental PS samples were prepared by anodizing p-type (100) Si wafers (0.01~0.02 Ω cm) in an ethanoic HF solution at a current density of 50 mA/cm^2 for 0.5~2.5 min. After anodization, self-supporting PS layers were obtained by an electrochemical peeling method. The samples were partially oxidized by rapid thermal oxidation for 2~5 min at 700℃ in a dry oxygen. Finally, thin Au films (10 nm thick) were evaporated on the both sides of the PS layer, and used as the electrodes.

For characterization of transport process in PS, we have used a TOF technique as shown in Fig. 1. A dc bias voltage V_{PS} was applied to the back electrode with respect to the semitransparent Au electrode on the illumination side. To generate electrons in the region very close to the electrode, an UV light pulse (5 ns pulsed nitrogen laser with a wavelength of 337 nm) was used for excitation. The transient behavior of the induced photocurrent was observed with a digital oscilloscope. From this measurement, the $\mu\tau$ product of electrons was evaluated at various applied voltages, where μ and τ are the mobility and the lifetime, respectively.

3. Results and Discussion

Fig.2 shows the transient photocurrent after a 5 ns light pulse incidence for a 25 μm thick self supporting PS sample at different applied voltages. In all cases, the photocurent shows a nearly exponential decay. This behavior is quite different with that of amorphous silicon where the transient curve shows decay as t^{-n}. Also the result of Fig. 2 is totally different with that of c-Si in which the TOF signal is observed as a single current pulse. There should be an characteristic transport mode in nanocrystalline PS, since the TOF curve implies that hot and/or quasiballistic electrons component are involved in the transport process.

The experimental result suggests that photogenerated electrons are captured by traps due to interfacial states of silicon nanocrystallites with a capture probability given by an inverse of time constant. When the transient curves in Fig. 2 are represented as $I(t) = A\exp(-t/\tau)$, where A is constant, τ can be regarded as the electron lifetime at the respective applied voltages. We can determine how the electron drift length in PS is enhanced without any scattering loss as a function of applied voltage as follows.

A $\mu\tau$ product deduced from TOF measurements at a given electric field F provide a value of the drift length L,

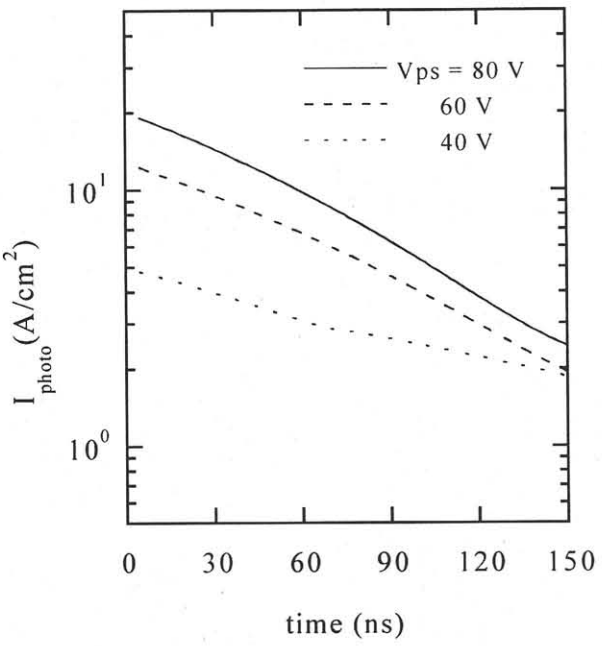

Fig. 2 Photocurrent transient measured by a TOF technique at three different valies of applied voltage V_{PS} for a 25mm thick self-supporting PS.

since the drift length is represented by $\mu\tau F$. This value corresponds to an average distance in which photoexcited electrons can move before trapping. The probability p that photoexcited electrons remain ballistic at a distance x from the electrode on the excitation side is given by

$$p = \exp(-x/L). \quad (1)$$

In the case that $\mu\tau F \ll d$, on the basis of Hecht formula [5], the integral of the transient photocurrent the collected charge on the opposite Au electrode, Q_0, is given by

$$Q_c = Q_0 \eta \frac{\mu\tau F}{d}, \quad (2)$$

where Q_0 is the charge corresponding to photogenerated electrons by an incident laser pulse, d is the distance between the electrodes, η is the quantum efficiency of free carrier generation. The $\mu\tau$ product can be deduced from the TOF characteristics of the collected charge for each applied voltage.

Table 1 shows the obtained values of the $\mu\tau$ product, the drift length L and the corresponding average energy gain of electrons E during the drift. The drift length L of electrons is significantly increased up to 2.5μm with increasing applied voltage. This is far from the maximum drift length of hot electrons in c-Si under an extremely high electric field.

The drift length in the region of V_{PS}>60 V are hundreds times larger than the mean size of Si nanocrystallites (2-3 nm in diameter) surrounded by thin oxide layers. Under the biased condition, major potential drop is produced only at the interfacial thin oxides. There is a periodic spike-like sequence of high electric field in the nanocrystalline PS layer. One possible transport mechanism in this situation is that electrons can travel for a long distance ballistically by multiple tunneling through neighboring Si nanocrystallites with little energy loss, though the details are yet to be clarified.

Table 1. Mobility-lifetime product $\mu\tau$, drift length L and average energy of electrons E deduced from TOF results in comparison to applied voltage V_{PS}

V_{PS} (V)	$\mu\tau$ (cm^{2}V^{-1})	L (μm)	E (eV)
40	3.7×10^{-9}	0.6	0.84
60	6.7×10^{-9}	1.6	3.8
80	7.8×10^{-9}	2.5	8.0

Under a sufficient electric field, the average energy gain of electrons in nanocrystalline PS reaches 3~8 eV which is considerably higher than those of both thermalized electrons and hot electrons generated during conventional transport in solids. This is consistent with the previously reported energy distribution of electrons emitted from the PS diodes to vacuum [3]. Also, when TOF measurements are carried out in vacuum, it has been confirmed that electrons are emitted through the opposite Au electrode with similar high energies of several electron volts.

According to the estimation from the result of Table 1, the probability that an electron remains ballistic at a distance of 5μm from the Au electrode on the illumination side is 14%. This proves efficient generation of ballistic electrons in nanocrystalline PS layers.

4. Conclusion

The peculiar carrier transport characteristics in self-supporting nanocystalline PS films have been clarified by a TOF technique. Under a high electric field, the drift length of electrons in PS is enhanced up to 2.5μm that is hundreds times larger than the size of Si nanocrystallites. The nanocrystalline silicon layer acts as a ballistic transport medium. Besides optoelectronic applications, this material is also useful as a key component in the solid state ballistic devices.

References

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