Correlation Between Lateral Photovoltaic Effect and Conductivity in *p*-type Silicon Substrates

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The lateral photovoltaic effect (LPE) can be observed in semiconductors by irradiating a light spot position between electrodes on sample's surface. Because lateral photovoltaic voltage (LPV) is sensitively changed by light spot position, a LPE device has been tried as a position-sensitive detector. This study discusses the correlation between LPV and conductivity in *p*-type silicon and nano-structured Au deposited *p*-type silicon (nano-Au silicon), respectively. Conductivity measurement of the sample was carried out using the four-wire method to eliminate contact resistance, and conductivity dependence on LPV was simultaneously measured by changing the light irradiation position. The result showed a strong correlation between conductivity and LPV in the *p*-type silicon sample. The correlation coefficient was 0.87. The correlation coefficient between LPV and conductivity for the nano-Au silicon sample was 0.41.

Key Words : Lateral photovoltaic effect (LPE), Lateral photovoltaic voltage (LPV), Conductivity, Correlation coefficient, Four-wire method

Introduction

The lateral photovoltaic effect (LPE) has been popularly used in semiconductor systems[1] since it was first discovered.[2] Lateral photovoltage (LPV) originates from the difference in charge population caused by light irradiation due to an asymmetric charge diffusion.[3] LPV output changes linearly with the change in the light irradiation position. Therefore, in order to develop LPE as a position-sensitive detector, efforts have been made to improve LPV and LPV sensitivity with the change in light position.[4-6] Recently, metal-semiconductor (MS)[7,8] and metal-oxide-semiconductor (MOS)[3,5,9,10] systems have been studied widely in an effort to improve LPV sensitivity. It was proven experimentally that LPV sensitivity is determined by several critical factors such as distance between electrodes, material selection, power and wavelength of the light source, and metal thickness, in case of MS and MOS systems.[3] The mechanism of LPE has been interpreted by the carrier diffusion theory,[3,11] which can explain LPV sensitivity dependence on the aforementioned factors. However, there can be other factors that determine LPE and LPV sensitivity. This is because the reported mechanism is oversimplified by considering only carrier diffusion. Carrier transport can easily be influenced by a subtle change in the electrical circumstance in a sample during the LPE process. For example, any change in the internal electrical field of a sample has an impact on LPV sensitivity.[11] In order to further investigate unclear mechanisms in the LPE process, it is necessary to monitor another electrical property of a sample during the LPE process. For example, correlation between electrical conductivity and photovoltage was mainly investigated in a solar-cell[12] and in an inorganic light-emitting device.[13]

Here, we investigated the correlation between LPV and conductivity in a *p*-type silicon system using the four-wire conductivity measurement during the LPE process. We were able to measure the conductivity of a pure sample using the four-wire measurement without the effect of contact resistance between the sample and the electrodes. Meanwhile a halogen lamp light was used to irradiate the surface of the sample, with changes in the light position. Thus, we simultaneously monitored LPV and conductivity and demonstrated the correlation between LPV and conductivity attributable to the change in the internal electrical field of the sample. In addition, the correlation between LPV and the conductivity of nano-structured Au deposited *p*-type silicon (nano-Au silicon) was also demonstrated.

Experimental

A piece (3 mm × 4 mm × 0.25 mm) of *p*-type silicon (100) was cleaned by ethanol and de-ionized (DI) water in a sequence and was thoroughly dried with N_2 gas. Four silver wires (Model No. AG005840, GoodFellow, Inc.) were used as electrodes by attaching them on the surface of the sample using a silver paste. We maintained a distance of 3 mm between the voltage HI (V+) and the voltage LOW (V−) electrodes. Four-wire current & voltage (I-V) measurements were carried out using a programmable current source (220, Keithley Instruments, Inc.) and a nanovolt-meter (2182A, Keithley Instruments, Inc.). A rectangular shaped (1 mm × 3 mm) lens focused the light that was irradiated on the sample by a halogen lamp (135 W, LS-F100HS, Seokwang Optical Co., Ltd.) (See *Supporting Information*). A piece (3 mm × 4 mm × 0.25 mm) of nano-Au silicon was fabricated using an electroless method, wherein a *p*-type silicon was dipped into

a solution of 0.5 M HF for 1 min with 2 mM $HAuCl_4$. Four-wire current & voltage (I-V) measurements during the LPE process of the nano-Au silicon were carried out similar to the measurement in the *p*-type silicon sample. All experiments were carried out at ambient conditions.

Results and Discussion

p-**Type Silicon.** Figure 1 shows the dependence of LPV on the light irradiation position in the *p*-type silicon sample. When the light irradiation position is middle of the V+ and V− electrodes, LPV is almost zero. LPV shows negative and positive values as the light irradiation moves close to the V+ electrode and the V- electrode, respectively. LPV intensity decreases as soon as the light irradiation position comes into electrode regions; this results from the reduced light intensity in electrode regions. As similar as previously reported behavior of LPV,[14] polarization of LPV is switched by gradually changing the light irradiation position from the V+ electrode to the V- electrode. The switched LPV curve is non-linear, as shown in Figure 1. Such a non-linearity of LPV was reported in the cases of long contact distance and vertical offset of irradiation position.[3] LPV non-linearity can

be produced by a sample having higher resistivity.[3]

Dependence of conductivity on LPV intensity is shown in Figure 2. Conductivity of the *p*-type silicon was measured using the four-wire method while measuring the LPV. The conductivity was determined by the slope of the I-V curve, and LPV was estimated by an offset of the I-V curve (See *Supporting information*). Conductivity tends to increase as LPV intensity increases. The red line in Figure 2 represents a linearly fitted line of conductivity in relation to the LPV intensity. The slope of the linearly fitted line is 6.1×10^3 S/(cm·V). In addition, the Pearson product-moment correlation coefficient[14] is 0.87. This means that a strong linear relation exists between conductivity and LPV intensity in the *p*-type silicon sample. LPV is caused by a difference in the charge population during light irradiation. The unbalanced charge population at the V+ and V− electrodes can cause a potential difference in the *p*-type silicon. This potential difference can enhance the internal electric field. As the induced LPV intensity is larger, greater enhancement in the internal electric field of the *p*-type silicon sample is expected. Because of the enhanced internal electric field, the mean free time of the charge carrier in the *p*-type silicon increases, as a charge carrier in a higher internal electric field tends to be less scattered by collisions with the other charge carriers.[15] Conductivity increases with the increased mean free time. Therefore, conductivity of the *p*-type silicon increases as LPV intensity increases.

Nano-Structured Au Deposited *p*-type Silicon (Nano-Au Silicon). An improvement in the LPV sensitivity by using nano materials such as quantum dot and graphene has been reported recently. We introduced Au nano features on the *p*-type silicon substrate and monitored the correlation between conductivity and LPV in a manner similar to the *p*-type silicon experiment. The configuration of electrode connections to the sample is shown in the inset of Figure 3. Four Ag wires were connected to the Au nano features film. The nano features of Au were deposited on the *p*-type silicon by an electroless method.[17] The inset SEM image in Figure 3 is a top-view image of the Au nano features on the *p*-type
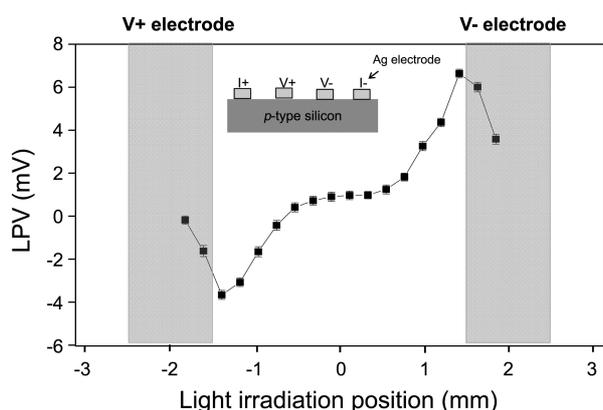

Figure 1. Dependence of LPV on the light irradiation position in the *p*-type silicon. The gray colored boxes represent the V+ and V− electrodes, having a width of 1 mm. Inset: scheme of a *p*-type silicon sample for LPV measurement.
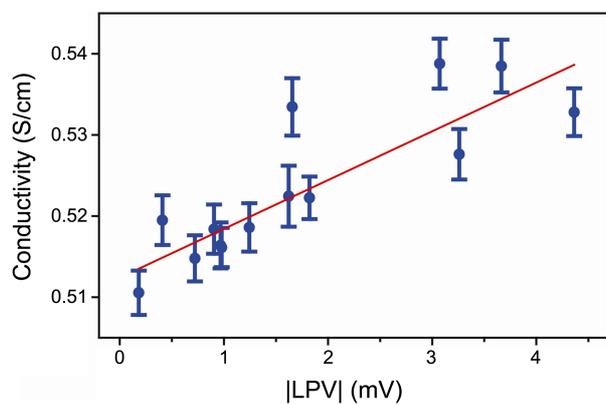

Figure 2. Conductivity of *p*-type silicon during LPE process. The red line is a linearly fitted line.
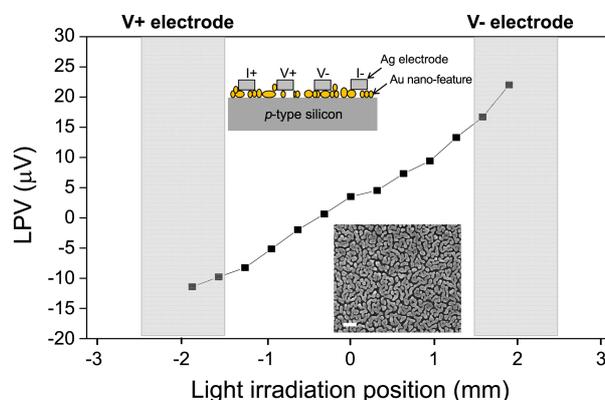

Figure 3. Dependence of LPV on the light irradiation position in the nano-Au silicon. The gray colored boxes represent the V+ and V− electrodes, having a width of 1 mm. Insets: scheme of the nano-Au silicon sample for LPV measurement and SEM image of the nano-Au silicon sample (top view image, scale bar: 200 nm).
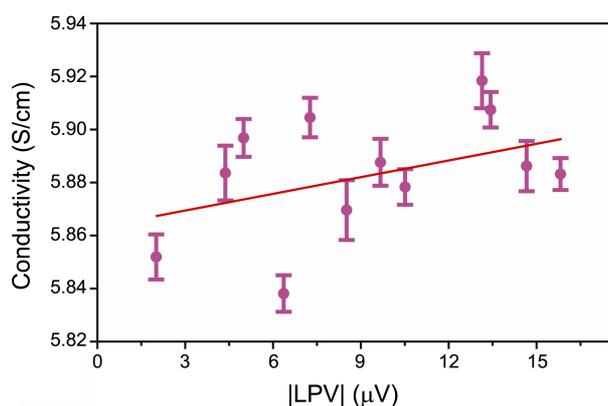
Figure 4. Conductivity of nano-Au silicon during the LPE process. The red line shows a linear fit.

silicon substrate. Most of the Au nano features are discrete, while some are entwined with one another. Gaps between the Au nano features are less than 100 nm. The degree of separation and elongation can be controlled by manipulating the deposition time of the Au nano feature.[17] LPV of the nano-Au silicon shows a similar switch of polarization as light irradiation position changes from the V+ electrode to the V− electrode. Maximum LPV intensity is about 20 mV; a few hundred times lower than that of the *p*-type silicon. The LPV curve is more linear as compared to the *p*-type silicon LPV curve. In a typical MS system, LPV non-linearity is higher in samples with low conductivity.[3] Conductivity of the nano-Au silicon is an order of magnitude higher than that of the *p*-type silicon, as shown in Figure 4.

Figure 4 shows dependence of conductivity on LPV intensity for the nano-Au silicon. The conductivity increases as LPV intensity increases. The slope of the linearly fitted line (the red line in Fig. 4) is 2.1×10^3 S/(cm·V). However, the Pearson product-moment correlation coefficient of the nano-Au silicon is 0.41. A weaker correlation between conductivity and LPV than for *p*-type silicon is observed. In a typical MS system, metal thickness can affect maximum LPV intensity.[3] Because carrier diffusion is poor in thin metal films, it causes a small carrier population difference at (+) and (−) electrodes (that is LPV). Thick metal films have good carrier diffusion. Small carrier population difference at the electrodes can also be caused if the diffusion is excessively rapid. Therefore, to have an appropriate carrier population difference at the electrodes, a metal film having an optimized thickness should be used.[3] Because carrier diffusion in the Au nano features of the sample is inferior to a thin Au film, the carrier population difference at each electrode of the Au nano features deposited on the *p*-type silicon is lower than that of the Au film. The maximum LPV intensity (20 mV) of the sample is much lower than that of a typical MS system (~10 mV).[7,8] This small LPV does not enhance the internal electric field much. As a result, a weaker correlation between conductivity and LPV than in the case of *p*-type silicon is observed.

Conclusion

In conclusion, we successfully demonstrate that conductivity increases with increase in LPV intensity in the *p*-type silicon and the nano-Au silicon. The correlation between conductivity and LPV is stronger in samples having higher LPV intensity. Au nano features were introduced in semiconductor systems in order to utilize metal nano-structures similar to a metal film in an MS system. A systematized experiment would be performed later to confirm the effect of Au nano features in a semiconductor system during the LPE process.

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