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ABSTRACT
Probing dopant distributions in nanoscale devices may find important applications in failure analysis. In this work, we employed cryogenic electrostatic force microscopy (EFM) to probe the dopant distribution in a lateral nanoscale bipolar junction transistor formed by ion implantations. The photocurrent characteristics under light illumination show that the devices were made properly. The distributions of phosphorus and boron dopants are visible in the phase domain of EFM when the operating temperature is lowered to 130 K from room temperature. Numerical simulations show that the phase shifts for the doping regions are largely consistent with the experimental data.

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The functionality of semiconductor devices is essentially determined by dopants in the semiconductor. The dopant profile in lateral dimension confines the device structure. The traditional method of measuring the distribution of shallow dopants is scanning tunneling microscopy (STM), but it can only detect several atomic layers on the top layer. Another method is time-of-flight secondary ion mass spectrometry (TOF-SIMS). Unfortunately, its lateral resolution is limited and the samples are often destroyed during the profiling process. Electrostatic force microscopy (EFM) is nondestructive but suffers from low sensitivity, which can be improved by lowering the operating temperature.

Here, we employ EFM to probe the junction doping profile in nanoscale pnp bipolar phototransistors (BPTs). BPTs are fabricated by properly doping the device layer of a silicon-on-insulator (SOI) substrate. At room temperature, the EFM sensitivity is low because of the screening effect created by free-moving electrons, leading to larger electrostatic force fluctuation. The sensitivity can be improved by lowering the operating temperature to 130 K. With −3 V and +3 V bias on the cantilever, the EFM probes the doping profile in our device by inducing phase shifts. Additionally, we find that the absolute phase shift at 130 K is more than 10 times larger than that at room temperature.

To avoid the introduction of possible artificial effects to the phase image by the uneven surface topography, we fabricated planar bipolar phototransistors by doping the device layer of a silicon-on-insulator (SOI) wafer, as shown in Fig. 1. The device layer of the as-purchased SOI wafers is p-type and has a resistivity of 20 Ω cm, meaning that the boron doping concentration is approximately $10^{15} \text{cm}^{-3}$. For a bipolar phototransistor, the doping concentration in the collector region should be as low as possible to minimize the Early effect. Here, we used the lightly doped p-type device layer as the collector. This choice has dictated the fact that only PNP bipolar phototransistors can be made. In a properly designed bipolar phototransistor, the n-type base region is normally doped at a concentration 1–2 orders of magnitude higher than the collector. It is known that the gain of bipolar phototransistors is proportional to the doping concentration ratio of emitter to base. The doping concentration for the emitter is designed at a level of $10^{19} \text{cm}^{-3}$ as to ensure high photo gain for the device.

The device fabrication procedure is illustrated in Fig. 1(a). We used electron beam resist hydrogen silsesquioxane (HSQ) as the doping mask for the collector region, which can be turned into SiO$_2$ after electron beam exposure. The rest of the wafer was doped at a
The actual phosphorus doping concentration in the $n$-type base region is found as $8 \times 10^{16} \text{ cm}^{-3}$ (triangles). The subcollector is highly doped to facilitate Ohmic contacts between the metal electrode and the lightly doped collector. The Ohmic contact resistance is found as low as $\sim 20 \text{ }\Omega$ from Fig. 1(c).

For the planar device structure, the $p$-type collector and emitter are separated by the $n$-type base [Fig. 1(a)]. Photocurrent flows from the emitter to the collector through the short (red solid arrows) and long base (black dashed arrows) in parallel. It is known that a bipolar phototransistor has no gain unless the base length is much shorter than the minority diffusion length in the base. The expected minority carrier diffusion length in the base region of our device is on an order of micrometers. As a result, the photocurrent of our planar BPT dominantly flows through the short channel (red solid arrows). To investigate the impact of the short channel, we fabricated an array of such devices by varying the short base length from 100 nm to 500 nm.

Devices with the base length of 100 nm, 400 nm, and 500 nm were successfully calibrated. For each base length, we recorded the device dark current and photocurrent at different light intensities. Figure 2(a) shows the dark and photocurrent of the bipolar phototransistor with the base length of 100 nm. The dark current is relatively high due to the multiple leakage current flow paths [Fig. 1(a)]. Under light illumination ($\lambda = 532 \text{ nm}$), electron and holes are generated in the lightly doped collector region which is mostly depleted at a bias of $\sim 1 \text{ V}$. The electric field in the depleted collector will separate the photogenerated electron-hole pairs, injecting the electrons into the base region. As a result, the base potential is reduced. A large number of holes from the highly doped $p$-type emitter flow across the short base (red solid arrows), creating an amplified photocurrent collected by the subcollector. We also performed numerical simulations using the commercial software Lumerical, finding that the experimental and simulation results are largely consistent. Figure 2(b) shows the photocurrent as a function of light illumination intensity for devices with different base lengths. For the phototransistor with a base length of 100 nm, the photocurrent is linear with the light illumination intensity. The other two devices with longer base lengths show a sublinear relation. It is probably because the photocurrent that passes through the short base becomes dominant [red arrows in Fig. 1(a), panel (iv)] and the impact of the side path (black dash arrows) is negligible.
To visualize the device structure, we employed cryogenic electrostatic force microscopy (EFM, Japan Precision VIX) to probe the lateral spatial distribution of B and P dopants. The n-type device layer and the p-type handling substrate are both grounded, whereas the metal tip of the atomic force microscopy (AFM) is electrically biased, as shown in Fig. 3. The EFM images of a bipolar phototransistor with 200 nm base length are shown in Fig. 4. The topography of the device is nearly flat except surface roughness created by the bombardment of ion implantation [Fig. 4(a)]. In the phase scan, the tip is lifted up 50 nm and follows the same line profile in the topographical scan. At zero bias, no phase contrast is detected among different doping areas in the silicon substrate [Fig. 4(b)], which is not surprising. Note that the EFM phase change \( \Delta \phi \) is governed by the following equation:

\[
\Delta \phi = -\arcsin \left( \frac{Q d^2 C}{2k dz^2 (\Delta U)^2} \right),
\]

where C, z, and \( \Delta U \) are the capacitance, distance, and voltage between the cantilever and the sample, and Q and k are the quality factor and the spring constant of the cantilever, respectively.

Clearly, the phase shift is dependent on the bias voltage on the cantilever and the capacitive term \( \frac{d^2 C}{dz^2} \). At zero bias, no phase shift will be observed, consistent with what we observed in Fig. 4(b). At a fixed voltage bias and distance between the tip and the substrate, the capacitive term will be a function of local
substrate properties that the cantilever is probing, including the type and concentration of dopants and surface states. With a $-3 \text{ V}$ bias on the cantilever, we detected a clear positive phase contrast of the $p^+$ region against the $n$ region. When the voltage bias on the cantilever is switched to $+3 \text{ V}$, the phase contrast is flipped accordingly. This observation is consistent with our numerical calculations as the black dashed line ($n$-type) and red solid line ($p^+$-type) in Fig. 5(a). However, the phase image shows no contrast between the $n$-type region and lightly doped $p^+$-type region at both positive bias and negative bias [Figs. 4(c) and 4(d)] although our calculations show some phase contrast between these two regions at negative bias [Fig. 5(a)]. This inconsistency is probably caused by the screening effect of charged surface states that were not taken into consideration in our calculations. At low temperature, surface states will be neutralized. It is not surprising to observe that the aforementioned inconsistency disappears when the temperature is lowered to 130 K [compare the experimental data in Fig. 4(e) and the calculated results in Fig. 5(b) at a bias of $-3 \text{ V}$]. Additionally, the absolute phase shift becomes more than 10 times larger when the operating temperature is lowered from 300 K to 130 K [Fig. 4(f)] because the cantilever quality factor increases as the temperature decreases.

In conclusion, the nanoscale npn bipolar phototransistors (BPTs) were fabricated by properly doping the device layer of a silicon-on-insulator (SOI) substrate. To investigate the impact of the base, we fabricated an array of such devices in which the base lengths were 100 nm, 400 nm, and 500 nm. For the base length of 100 nm, the photocurrent is linear with the light illumination intensity. The base, we fabricated an array of such devices in which the base lengths were 100 nm, 400 nm, and 500 nm. For the base length of 100 nm, we detected a clear positive phase contrast between $n$-type doping ($10^{17} \text{ cm}^{-3}$), lightly doped $p$-type ($10^{15} \text{ cm}^{-3}$), and heavily doped $p$-type ($10^{17} \text{ cm}^{-3}$), respectively.

See the supplementary material for the simulations of electrostatic force microscopy.

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