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Impact of a few dopant positions controlled by deterministic single-ion doping on the transconductance of field-effect transistors

Masahiro Hori,[1] Takahiro Shinada,[2,a)] Yukinori Ono,[3] Akira Komatsubara,[1] Kuninori Kumagai,[1] Takashi Tanii,[1] Tetsuo Endoh,[4] and Iwao Ohdomari[1]
[1]*School of Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan*
[2]*Waseda Institute for Advanced Study, Waseda University, Shinjuku, Tokyo 169-8050, Japan*
[3]*NTT Basic Research Laboratories, NTT Corporation, Atsugi, Kanagawa 234-0198, Japan*
[4]*Center for Interdisciplinary Research, Tohoku University, Sendai 980-8578, Japan*

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As semiconductor device dimensions decrease, the individual impurity atom position becomes a critical factor in determining device performance. We fabricated transistors with ordered and random dopant distributions on one side of the channel and evaluated the transconductance to investigate the impact of discrete dopant positions on the electron transport properties. The largest transconductance was observed when dopants were placed on the drain side in an ordered distribution; this was attributed to the suppression of injection velocity degradation on the source side and the uniformity of the electrostatic potential. Thus, the control of discrete dopant positions could enhance the device performance. © *2011 American Institute of Physics*. [doi:10.1063/1.3622141]

The doping of impurity atoms in semiconductor devices is essential for adjusting the device parameters by controlling the electrical properties of the semiconductor materials. So far, it has been assumed that a semiconductor in the active channel region is doped homogenously. However, in nano-scale semiconductor devices, the assumption of uniform dopant distribution is not valid. As device dimensions are scaled down, the number of dopant atoms in the channel region decreases. The gate length of metal-oxide semiconductor field-effect transistors (MOSFETs) is set to approach 10 nm by the year 2020,[1] so for a typical concentration of 10^{18} cm^{-3}, the active channel region will contain only a few dopant atoms. Thus, the placement of individual dopant atoms significantly affects the electrical properties of devices.

Previously, we fabricated semiconductor devices with ordered dopant arrays using single-ion implantation (SII),[2–9] which enables us to implant dopant atoms one-by-one. The single-ion detection efficiency was 100%,[7,9] and the aiming precision was about 60 nm.[5] These studies revealed experimentally that controlling both the number and positions of dopant atoms is essential for suppressing device-to-device fluctuations in threshold voltage, which are due to random dopant fluctuations (RDFs).[4,5] Although several theoretical analyses of RDF effects have been presented since the 1990s,[10–15] experimental studies have been few, and the impact of individual dopant positions on device electrical properties is not completely understood. In this study, we fabricated transistors with dopants on the drain side of the channel in discrete ordered or discrete random distributions using the SII technique (see Figure 1) and evaluated the transconductances of four types of transistors with different dopant configurations achieved by interchanging the source and drain terminals. Electrical measurements revealed that controlling discrete dopant positions can improve electron transport.

Figure 2 shows the flow diagram for experimentally evaluating the influence of a few discrete dopant positions on transconductance. Transistors were fabricated on n-type (100) silicon-on-insulator substrates and patterned using standard photolithography. The channel widths were 100, 250, and 500 nm; the lengths and thicknesses were 500 and 90 nm, respectively, for all devices. The drain current (I_d) was controlled by the gate bias (V_g) from the substrate through the 125-nm-thick buried oxide. The device shows

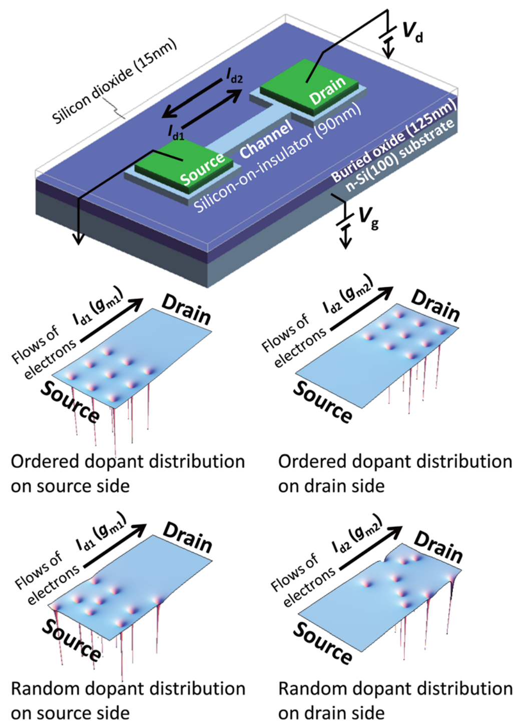

FIG. 1. (Color online) Illustration of device structure (top) and dopant configurations in the channel region (bottom). The drain current (I_d) is controlled by the gate bias (V_g) from the substrate thorough the 125-nm-thick buried oxide. Phosphorus ions are aligned on one side of the channel using single-ion implantation.

[a)]Electronic mail: shinada@aoni.waseda.jp.

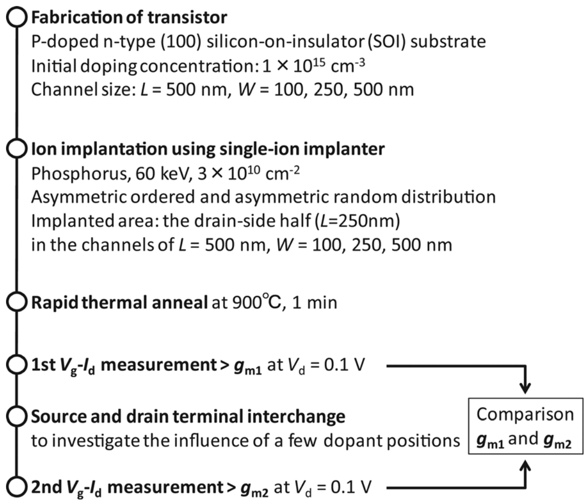

FIG. 2. Flow diagram for the experimental evaluation of the influence of asymmetric ordered and asymmetric random dopant distributions on the transconductance. We evaluate g_{m1} and g_{m2}, which are the transconductances for devices with dopants on the source side and drain side, respectively, by interchanging the source and drain terminals.

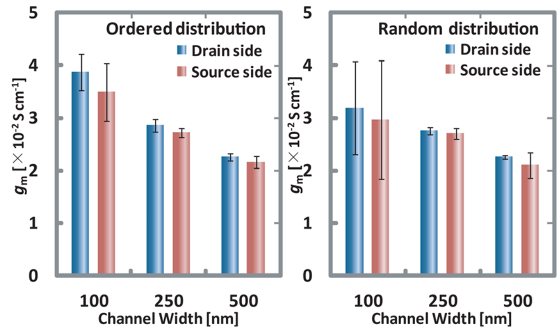

FIG. 4. (Color online) Bar chart of g_m for devices with different channel widths. The largest g_m value is observed when dopants are placed on the drain side in an ordered distribution. The error bars on the bar chart data indicate the device-to-device fluctuations. Six devices were measured for each size and condition. The device-to-device fluctuations in g_m for devices with dopants on the drain side in an ordered distribution are smaller than those for devices with dopants on the source side in a random distribution.

accumulation-mode n-type transistor operation. Doubly charged phosphorus ions (P) were implanted at 60 keV at a dose of 3×10^{10} cm^{-2}, yielding about 15 dopant atoms in the channel (100 × 500 nm). For devices with ordered dopant distributions, the phosphorus ions were implanted at 100 nm pitch. The transconductance (g_m) was obtained from the slope of the linear region of the I_d–V_g plot (dashed line in Figure 3). All results were obtained for 0.1 V drain voltage (V_d).

Figure 3 shows the typical I_d–V_g characteristics of FETs with asymmetric ordered and asymmetric random dopant distributions. All the I_d–V_g characteristics of devices with discrete ordered and discrete random dopant distributions aligned on one side of the channel showed deviations in the drain current when the source and drain were reversed. This asymmetry of the I_d–V_g characteristics could be attributed to the asymmetric dopant distribution.

Figure 4 shows a bar chart of g_m for devices with dopants on the source and drain sides in ordered and random distributions. The g_m values were normalized by the channel width (W). As W narrowed, the average g_m increased because of the greater effectiveness of electrostatic gate control in the FETs. The largest g_m was observed when dopants were placed on the drain side in an ordered distribution. The g_m values for devices with dopants on the drain side in an ordered distribution were, on average, 23.4% larger than those for devices with dopants on the source side in a random distribution. This is because of the suppression of injection velocity degradation on the source side and the uniformity of the electrostatic potential due to the ordered dopant distribution. The results show that the average g_m for devices with dopants on the drain side is always larger than that for devices with dopants on the source side. The theoretical study[14] shows that the presence of dopant atoms in the channel region strongly affects the local current density, because these atoms cause the accumulation of electrons injected from the source terminal on the source side of the dopant and their depletion on the drain side, resulting in a reduction in the velocity of electrons around the dopant. The current density on the source side is higher and more homogeneous when dopants are near the drain side of the channel. We believe that the increase in g_m for devices with dopants on the drain side results from the suppression of injection velocity degradation on the source side. The results show that the g_m values are larger for ordered than for random dopant distributions. The ordered dopant array forms a homogeneous potential distribution in the active channel region and thus forms a uniform current path. The current in the random

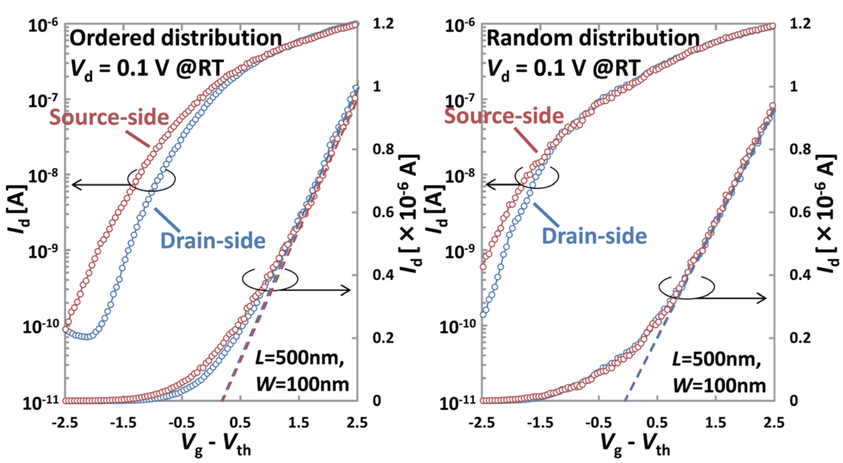

FIG. 3. (Color online) Typical I_d–V_g characteristics ($W = 100$ nm, $L = 500$ nm) for a device with an asymmetric ordered dopant distribution (left) and asymmetric random dopant distribution (right). All I_d–V_g characteristics showed deviations in the drain current when the source and drain terminals were interchanged. The transconductance is always larger when dopants are located on the drain side than on the source side.

dopant distribution percolates through the valleys in the potential landscape, resulting in a strong dependence of the location and magnitude of the potential valleys on the arrangement of the dopant ions.[5] We attribute this effect to the reduction in Coulomb scattering in the uniform potential distribution of the ordered dopant distribution. It is clear that g_m is sensitive to individual dopant locations and that control of individual dopant positions could enhance the electrical transport properties of the device.

Device-to-device fluctuations in g_m for devices with dopants on the drain side in an ordered distribution were reduced four-fold compared with those for devices with dopants on the source side in a random distribution ($W = 100$ nm). We attribute this to the high electron velocity in devices with dopants on the drain side, because the electrons in such devices are not scattered as strongly by impurities as those in devices with dopants on the source side. Thus, electron transport is strongly dependent on the injection velocity on the source side of the channel, and device-to-device fluctuations in g_m can be reduced by controlling the positions of individual dopant atoms on the drain side.

The impact of a few dopant positions on transconductance has been investigated experimentally by fabricating FETs with asymmetric discrete ordered and asymmetric discrete random dopant distributions. The SII technique was employed to control the number and position of dopant atoms in the active channel region deterministically. The g_m values for devices with a few dopant atoms on the drain side in an ordered dopant distribution are, on average, 23.4% larger than those for devices with dopant atoms on the source side in a random dopant distribution. We attribute this to the suppression of injection velocity degradation on the source side and the uniformity of the electrostatic potential due to the ordered dopant distribution. The device-to-device fluctuation in g_m could also be reduced by controlling the positions of individual dopant atoms on the drain side in an ordered dopant distribution. Small variations in individual dopant locations influence the electron transport properties significantly, and thus, the control of the number and position of dopant atoms in the active channel region can enhance device performances. These results contribute to extend doped-channel devices, which are necessary for controlling discrete dopant number and position ultimately using deterministic doping.[1]

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