P:04 TCAD analysis of discrete dopant effect on variability of tunnel field effect transistor

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Tunnel field-effect transistor (TFET) is a one of steep slope transistors that have gat- ed p-i-n diode structures. The gate voltage switches the band-to-band tunneling (BTBT) current between the source and the channel. The abrupt increase of BTBT current by the gate electrostatic control results in lower SS values than 60 mV/dec [1], and thus, TFET is expected to be a commercialized logic device in next generation. Recently, toward the cir- cuit application of TFETs, the variability of TFETs has been investigated [2]. The analy- sis of the mechanisms of variability is crucial for the suppression of the variability.

In this work, we numerically investigate the variability of the TFETs in the presence of random fluctuation of discrete dopant using TCAD simulation. We find the variation in the drain current of TFETs is suppressed by in- crease of the device width. Interestingly, we also find that the TFETs with discrete dopant distribution tend to show higher drain current compared to the TFETs with homogeneous dopant distribution. Although the discrete- ness of the dopants causes the variability, it can also amplify the operation current.

We considered silicon-on-insulator (SOI) p-TFETs with discrete dopant distributions. Figure 1 indicates a schematic figure of the TFET, and dimensions of the TFET are given in the right side of the figure. To reduce computational cost, we considered discrete dopant distribution only in the red shaded area beneath a gate as shown in Fig. 1, where the strong BTBT occurs.

In this work, the device simulations based on the drift diffusion approximation were performed by the three dimensional simulator HyENEXSS [3]. We implemented the gener- ation/recombination model arising from BTBT based on WKB approximation [4] into the simulator, which can treat non-uniform barrier potential along the tunneling path.

First, we calculated I_D-V_{GS} curves for 100p-TFETs that have different discrete dopant distributions each other. Figure 2 indicates 100 I_D-V_{GS} curves for source doping density, N_S = 1e20 cm^{-3}. The average of the current I_{AVE} and the relative standard deviation I_{DEV} at 1 V are shown in this figure. The I_D-V_{GS} curve for homogeneous dopant model is also cal- culated as a reference. We calculated similar I_D-V_{GS} curves for various device width, W_g= 6~30 nm, and plotted *I*DEV as a function of W_g in Fig. 3. As shown in this figure, I_{DEV} decrease with the increase of W_g. Of particular note is that the average current I_{AVE} is higher than that of continuum dopant model, as shown in Fig. 2. In order to clarify the mechanism of this enhancement, we investigated the effect of "localization" of the dopant density profile. We considered non-uniform density profile along the width direction (y axis) as shown in Fig. 4 (a) and calculated I_D. Fig- ure 4 (b) shows the I_D as a function of localization strength, r. This figure indicates the localization enhances the current even though the average dopant density is equiv- alent. Figure 5 (a) and (b) show the intensity of electric field E_X along the tunneling direction (x axis) at the source edge (x = 0.057μm). As can be seen from this figure, the electric field locally increases owing to the local increase of the dopant density. According to the Kane's BTBT theory [5], BTBT rate exponentially increases with respect to electric field applied to the tunneling carries. Therefore, the appearance of high dopant density region due to the discreteness of the dopant causes the local enhancement of the electric field, and the exponential increase of the current in such region results in the enhancement of the total current. Based on this analysis, we investigated the relation between I_D and strength of the localization in 100 samples. From the calculation results, we estimated the region where BTBT rate is high, and plotted I_D and the maximum dopant density in this region. As expected from the aforementioned analysis, we see a strong correlation between I_D and local increase of the dopant density.

In this paper, we have numerically investigated the variability of TFETs by using TCAD simulation. The variability of drain currents is suppressed by increase of the device width. We have also found that TFETs with discrete dopant distribution tend to show high drain currents compared to the current calculated from homogeneous dopant model.

We clarified that this current enhancement originates from the local increase of the electric field around discrete dopant position.

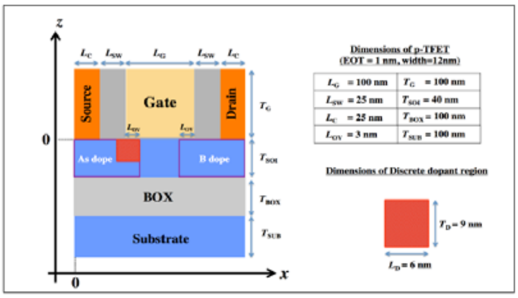

Fig.1. Schematic figure of TFET with discrete dopant distribution (shaded area).

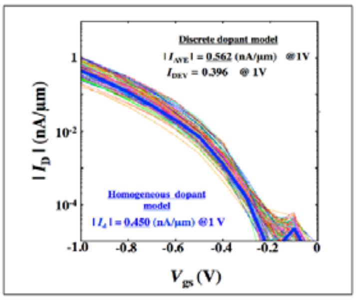

Fig.2. I_D-V_{GS} curves for 100 TFETs with discrete dopant distributions.

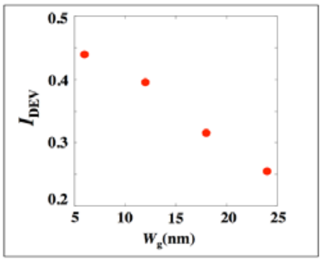

Fig.3. Relative standard deviations of drain currents I_{DEV} as a function of device width W_g.

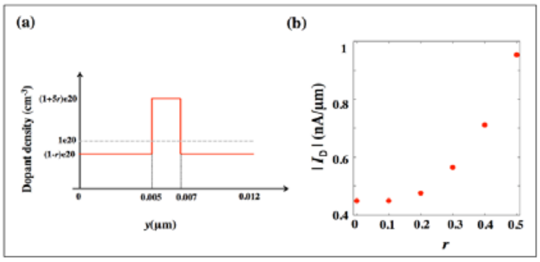

Fig.4. (a) Non-uniform dopant density distribution with localization strength r, and (b) drain current I_D, as a function of r.

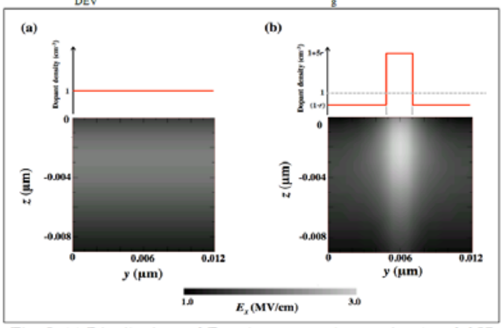

Fig. 5. (a) Distributions of E_x at the source edege region (x = 0.057 µm) of (a) uniform model and (b) non-uniform model.

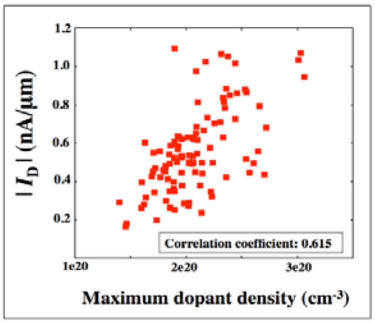

Fig. 6. Scatter plot of drain currents and maximum dopant density.

[1] W. Y. Cho et al., IEEE Electron Device Lett. 28, 743 (2007)
[2] N. Damrongplasit et al., IEEE Electron Device Lett. 34, 184 (2013)
[3] W. Vandenberghe *et al.*, J. Appl. Phys. 109, 124503 (2011)
[4] HyENEXSS, ver 5.5.7
[5] E. O. Kane, J. Appl. Phys. 32, 83 (1961)