Large-Scale "Atomistic" Approach to Discrete-Dopant Fluctuated Si Nanowire FETs

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Silicon (Si) field effect transistors (FETs) with vertical channel structures are promising candidates for next generation VLSI devices [1,2]. Impact of the discrete-dopant number and position on device performance is crucial for ultimate Si technologies [3,4]. In this paper, we for the first time study the electrical characteristic fluctuations in 16nm Si nanowire FETs. Discrete dopants are statistically positioned in the 3D channel region to examine associated carrier transportation characteristics, concurrently capturing "dopant concentration variation" and "dopant position fluctuation". The cylindrical-shaped-surrounding-gate nanowire FET shows its superior fluctuation immunity against discrete dopants over the square-shaped-surrounding-gate one. Even the latter exhibits similar threshold voltage (Vth) fluctuation with the former; the latter still has larger on- and off-state current fluctuations (about 2.2 and 8.8 times) than the former due to nonuniform (fringing) fields and current crowding phenomena.

All statistically generated discrete dopants, shown in Fig. 1, are incorporated into the large-scale 3D "atomistic" device simulation under parallel computing system, where a quantum mechanical transport simulation is performed [1]. Figure 1(a) shows 149 discrete dopants randomly distributed in 2000nm length cylinder (radius = 4nm) with an average concentration of 1.48×10^{18}cm^{-3}. The dopants may vary from 0 to 5, where the average number is 1, within its 125 sub-cylinders of 16nm length, (plots of (b), (c), and (d)). These sub-cylinders are then equivalently mapped into the channel region of nanowire devices for dopant position/number-sensitive simulation. Figure 2 shows a comparison of the 3D simulated on-state potential between the nominal (continuously doped) and discrete-dopant fluctuated cases. The discrete dopants positioned in the channel induce a relatively negative electric field and thus disturbs the current path. Figure 3 shows the Vth fluctuations and on-off-state current (I_{on} and I_{off}) of the 16nm cylindrical- and square-shaped-surrounding-gate devices, where Vth's fluctuation of the two nanowire devices is 4 times smaller than the single-gate FET, shown in Fig. 3(a). The latter has similar Vth fluctuation with the former; however, I_{on} and I_{off}'s fluctuations of the latter are 2.2 and 8.8 times larger than the former due to sensitively nonuniform field distribution and current crowding. Figure 4 shows the I_{on}-I_{off} characteristics. For cases with similar I_{on}, a maximum fluctuation of I_{off} is within 0.05 nA/um. Figures 4(b)-4(b''), 4(c)-4(c'), and 4(d)-4(d'') disclose three different discrete-dopant channels, having similar values of I_{on} or I_{off} but with various dopant positions. The cross-sectional on-state current density and off-state potential distributions extracting from the center of channel are examined. Figures 4(b')-4(b'') and 4(c')-4(c'') show the distribution of the on-state current. For the three different cases of the dopant, shown in Figs. 4(b)-4(d), Figs. 4(b')-4(d') exhibit different current distributions due to the discrete dopants appearing on the channel. The different conducting paths of devices result in different I_{on} even we have very similar I_{off}, shown in Fig. 4(a). For the device having very similar on- (or off-) state current with different off- (or on-) state situations, Figs. 4(b'')-4(d'') are the off-state potential distributions at the center of the device channel. As shown in Fig. 4(a), the device possesses very similar I_{on} (the vertical ellipse circled), but with different I_{off} (> 3 times) resulting from the different randomness of the dopant number and position, shown in Figs. 4(c'') and 4(d'').

In summary, we have explored the discrete-dopant-induced characteristic fluctuations of the 16nm nanowire devices using a large-scale 3D "atomistic" simulation technique. For the nanowire devices having similar Vth fluctuation, the on- and off-state current fluctuations of the square-shaped-surrounding-gate device are 2.2 and 8.8 times larger than the cylindrical-shaped- surrounding-gate nanowire FET. This study provides an insight into the problem of discrete-dopant-induced characteristic fluctuations in Si nanowire FETs.

References:

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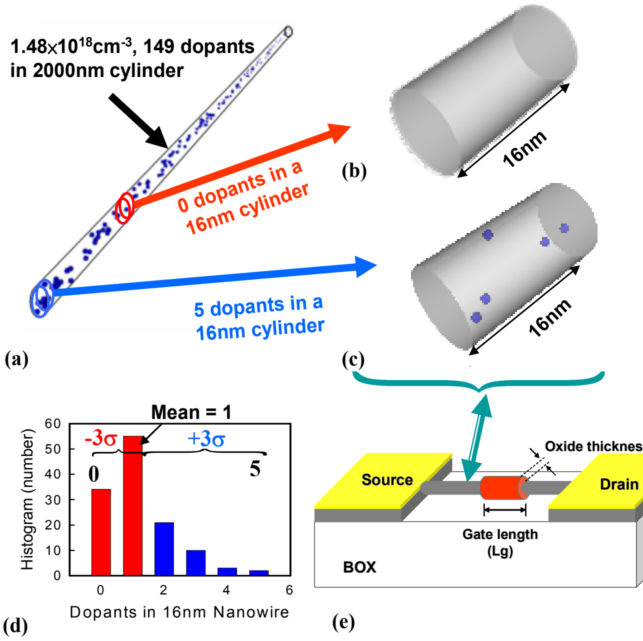
[3] Y. Li *et al.*, Jpn. J. Appl. Phys., **45** (2006) 6860-6865.
[4] A. Asenov *et al.*, IEEE Trans. Elec. Dev., **50** (2003) 1837-1852.

Figures:



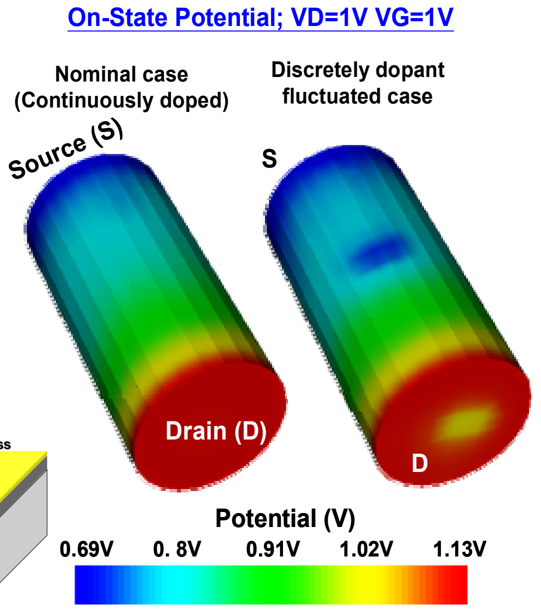


Figure 1. (a) Discrete dopants randomly distributed in 2000nm length cylinder (radius = 4nm) with the average concentration of 1.48x10^{18}cm^{-3}. There will be 149 dopants within the cylinder and dopants vary from 0 to 5 (the average number is 1) within its 125 sub-cylinders of 16nm length, (plots of (b), (c), and (d)). These sub-cylinders are then equivalently mapped into the channel region of nanowire FET for dopant position/number-sensitive simulation.

Figure 2. Comparison of the 3D simulated on-state potentials, the left distribution shows the result of nominal (continuously doped) case and the right one is discretely doped one.

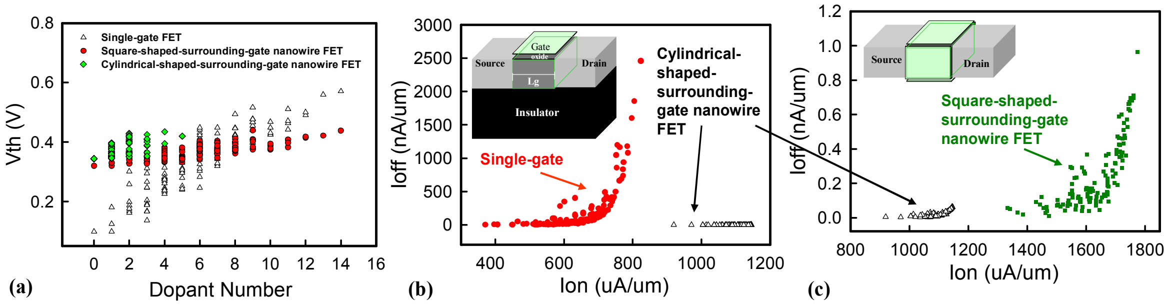


Figure 3. The fluctuations of (a) threshold voltage (Vth), and (b) and (c) on/off state current of the discrete-dopant fluctuated 16nm single-gate FET, square- and cylindrical-shaped-surrounding-gate nanowire FETs. The structure of single-gate and square-shaped-surrounding-gate are shown in the insets of (b) and (c) , respectively.

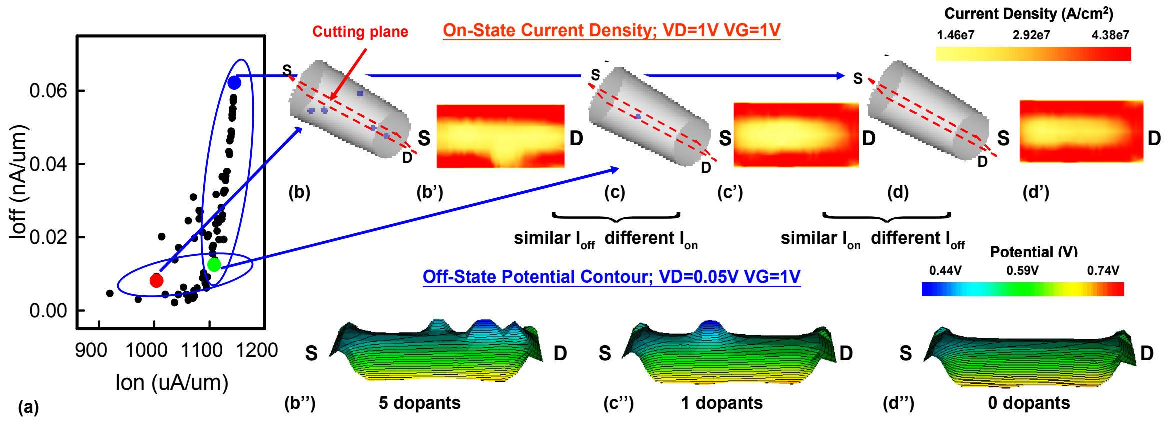


Figure 4. (a) Ion-Ioff characteristics of the 125 discrete-dopant 16nm cylindrical-shaped-surrounding-gate nanowire FETs. Three cases are selected to evaluate similar Ioff but different Ion ((b) and (c)) and similar Ion but different Ioff ((c) and (d). ((b)-(d)) and ((b')-(d')) show the cross-sectional on-state current density. ((b'')-(d'')) show the off-state potential contours. All of them are extracted at the center of the channel.