Width Dependence of RDD-Induced Current Fluctuation in Silicon Nanowire Transistors

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Fluctuation of device characteristics due to random discrete dopant (RDD) distribution is becoming a major concern for nanoscale transistors [1]. Effects of the RDD distribution are usually analyzed with a randomly generated dopant distribution. The actual RDD distribution, however, should be correlated with the process condition, and can be different from a mathematically generated one. We have studied the effects of RDD in silicon nanowire (Si NW) transistors with a square cross-section of 3 nm × 3 nm by using realistic implanted and annealed arsenic (As) distributions [2]–[4]. In this study, we investigate the effects of the NW size on the current fluctuation of NW transistors.

Discrete random As distributions in Si NWs are obtained using Sentaurus kinetic Monte Carlo (KMC) simulator [5]. Si NWs (w nm wide, w nm high, and 30 nm long) covered with 1 nm-thick SiO_2 and with a thick mask are implanted with As (0.5 keV, 2×10^{14} cm^{-2}) and annealed at 1000 °C with a hold time of 0 s [Fig. 1(a)]. For studying the effects of the NW size, we simulate two types of NWs of $w = 3$ nm and 5 nm. Statistical variations are investigated by using different discrete As distributions [Fig. 1(b)], which are generated by preforming the KMC simulation with different random seeds. The active As distributions obtained through the KMC simulation are introduced into n-type gate-all-around Si NW MOSFETs [Fig. 1(c)]. The drain-current–gate-voltage (I_d–V_g) characteristics are calculated by non-equilibrium Green's function method with an effective mass approximation [6]. The discrete impurities are treated with a cloud-in-cell charge assignment scheme.

Figure 2 shows histograms of a number of active As atoms in the Si NWs. We simulate 100 different discrete As distributions for each device structure. We find that about 30% of As atoms implanted into the Si region are active in the Si NWs. The average active As density in the source and drain (S/D) extensions is $N_{S/D} \approx 1.8\times10^{20}$ cm^{-3}. The standard deviation of $N_{S/D}$ is smaller for $w = 5$ nm, in accordance with the law of large numbers. Active As density profiles are plotted in Fig. 3. Dopant atoms diffuse into the channel region with the lateral abruptness of ~2.5 nm/dec, which causes large variability of the device characteristics [3].

Figure 4 shows calculated I_d–V_g characteristics at $V_d = 0.05$ V. We find that the I_d–V_g curves of the 5 nm NWs show larger fluctuation compared with those of the 3 nm NWs, especially in the lower V_g region. We also find that in the lower V_g region the log I_d-distribution for $w = 3$ nm is significantly asymmetric while that for $w = 5$ nm is fairly symmetric (see Figs. 5 and 6). The smaller I_d fluctuation for $w = 3$ nm is partially due to the short tail (virtually no tail) in the log I_d-distribution for the lower I_d side. This short tail may be attributed to the fact that the 3 nm NW transistor has better gate control compared to the 5 nm NW device.

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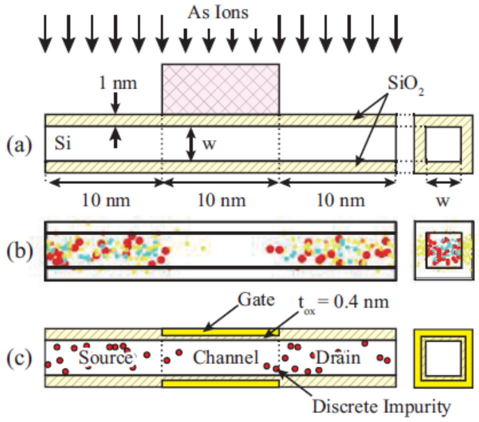

Fig. 1. (a) KMC simulation. (b) Discrete As distribution in the Si NW. Red dots show active As atoms in Si, light blue As clusters, orange As at the oxide/Si interface, and yellow As in the oxide. (c) Device structure for NEGF calculation.

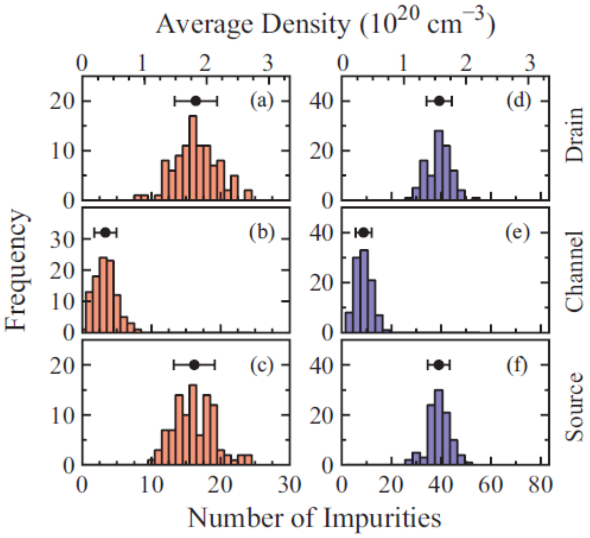

Fig. 2. Histogram of a number of active As atoms in the Si NWs of w = 3 nm (a, b, c) and 5 nm (d, e, f).

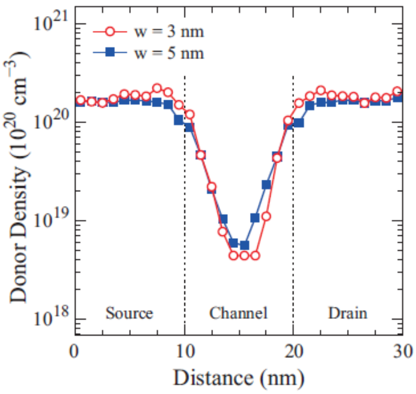

Fig. 3. Active As density profile along the source-to-drain direction for w = 3 nm (circles) and 5 nm (squares).

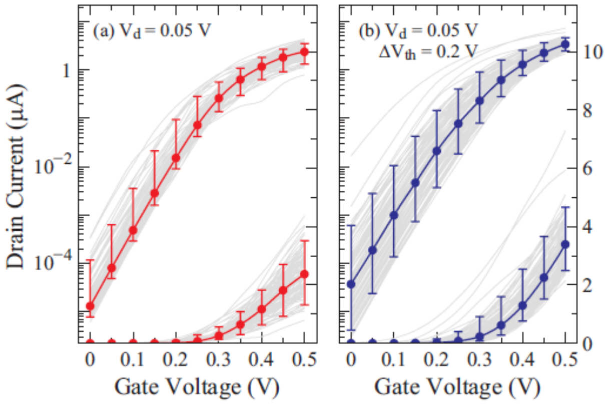

Fig. 4. I_d–V_g characteristics for w = 3 nm (a) and 5 nm (b). Close circles show the median ($I_{50\%}$). The upper error bars represent 95 percentile while the lower error bars represent 5 percentile values ($I_{95\%}$ and $I_{5\%}$).

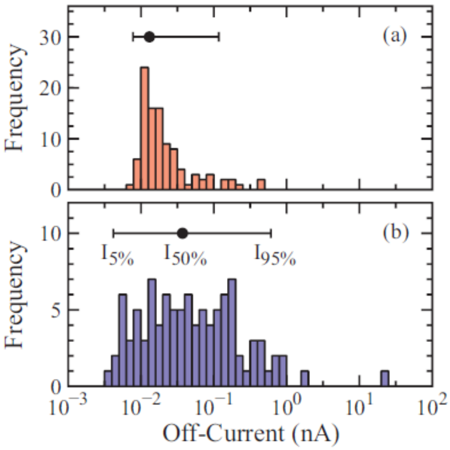

Fig. 5. Histogram of the off-current for w = 3 nm (a) and 5 nm (b) at V_d = 0.05V and V_g = 0.0 V.

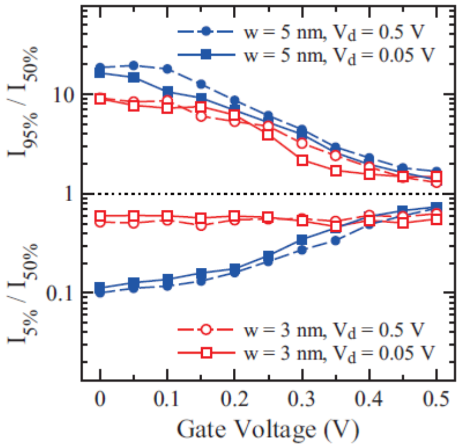

Fig. 6. $I_{95\%}/I_{50\%}$ and $I_{5\%}/I_{50\%}$ as a function of V_g. Open (closed) marks correspond to w = 3 nm (5 nm), and squares (circles) represent V_d = 0.05V (0.5 V).