Junction Leakage Variability Simulation Considering Random Discrete Dopants

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Abstract

Junction leakage current variability due to random discrete dopants (RDD) has been simulated. Quantum corrected coulomb potential has been considered for discrete dopants. The effect of the RDD profiles on the electric field and the trap assisted tunneling (TAT) current due to single discrete trap has been discussed.

Introduction

For low stand-by power ULSIs, junction leakage current and its variability is an important issue to be addressed [1]. Junction leakage current due to trap assisted tunneling (TAT) process is one of the main sources of such off-state leakage in high temperature. Thus, it is important to evaluate the variability of the TAT current for improving the reliability and yields of ULSIs.

TAT current fluctuation caused by the randomness of discrete trap number and location (Fig. 1) has been already simulated [2],[3]. On the other hand, it is well known that the randomness of discrete dopants (RDD) is a major cause of threshold voltage variation [4]. Therefore, RDD can also strongly affect TAT current variability. In this paper, we have numerically evaluated the TAT current variability considering the effects of RDD.

Simulation Method

In order to evaluate the TAT current variability due to RDD fluctuations, potential and carrier density profiles with RDD are calculated by a drift-diffusion simulation. Using the obtained device profiles, TAT junction leakage current is calculated based on the Shockley-Reed-Hall (SRH) model [5] (Fig. 2). About 4500 nMOSFETs with different RDD distributions were generated. Then, TAT current caused by a single discrete trap was calculated, while changing the position of the discrete trap within each FET. The energy level of the discrete trap was fixed at the mid-gap for evaluating the variability of the maximum TAT current caused by the electric field fluctuation due to RDD.

In order to represent the discrete dopant potential, an analytical effective potential model [6] is used as a quantum corrected coulomb potential. The cut-off radius, r_c, of the analytical effective potential model is calibrated to reproduce a quantum corrected coulomb potential (Fig. 4). In order to include the effects into the drift-diffusion simulation, the discrete dopant potential is converted into a doping density distribution based on Poisson’s equation in an isolated system.

Results and Discussions

Fig. 4(a) shows surface electric field profiles along the source-drain direction for devices with different RDD profile. The off-state electric field tends to be the highest around the surface of the channel/drain interface region, and the highest electric field varies about 2 times within the simulated devices. The highest electric field is obtained in device A, which has more discrete donors around the channel/drain interface (Fig. 4(b)). Because of the concentration of discrete donors around the channel/drain interface, the depletion region from the drain region reaches the channel region, and the large potential difference between the depletion region and the gate electrode causes the high electric field. Compared with device A, devices B (medium electric field) and C (low electric field) has fewer discrete donors around the channel/drain interface (Fig. 4(c),(d)).

Such electric field fluctuation by the difference of RDD profiles causes large difference in TAT junction leakage current calculated by the SRH model. Fig. 5 shows the distribution of J_{leak}, which is the maximum calculated TAT leakage current caused by a single trap for each device. J_{Leak} can vary about 2 orders of magnitude around the median value ($J_{\mathrm{Leak}}^{\mathrm{median}}$) by the electric field fluctuation due to RDD. These results show that RDD can accidentally cause extremely large junction leakage, and must be taken into account for leakage variability simulation, though the probability of such occurrence is low.

Conclusions

Variability of TAT junction leakage current due to RDD has been numerically evaluated. The TAT junction leakage current can be enhanced about 2 orders of magnitude from the median value because of the electric field enhancement caused by the discrete donor concentration in the channel region. Device structures should be designed considering such off-state leakage variability especially for low power ULSI applications.

References

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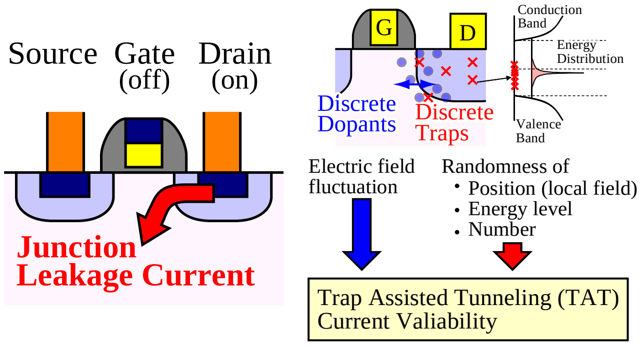


Fig. 1: Off-state junction leakage current fluctuation is investigated. Trap assisted tunneling (TAT) current is calculated as the junction leakage current in high temperature. The fluctuation of the TAT current can be enhanced by electric field fluctuation due to random discrete dopants (RDD) in addition to the randomness of discrete traps (trap position, density, energy level).

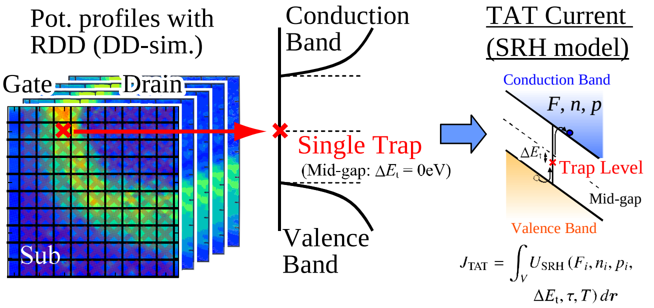
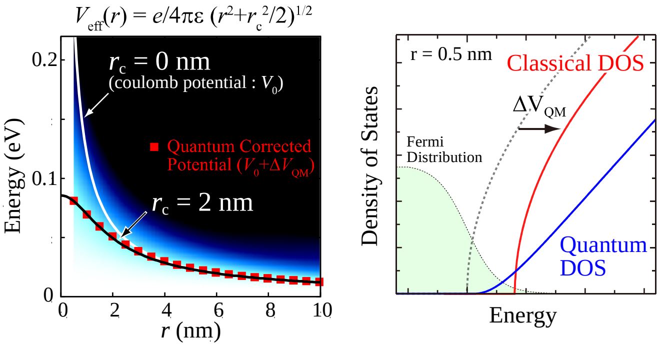
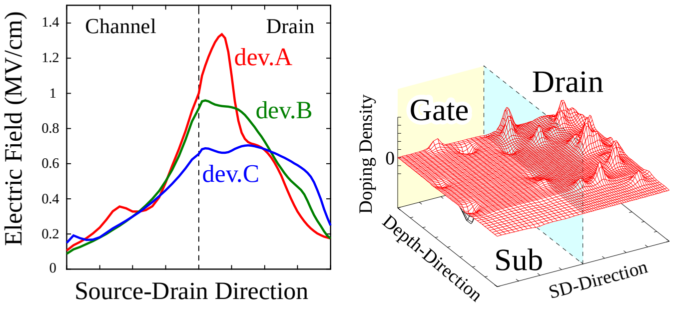


Fig. 2: Variability of TAT current due to electric field fluctuation caused by RDD is evaluated. In order to eliminate the randomness of discrete traps, TAT current due to a single discrete trap is considered. The single discrete trap is located at all mesh points of the potential profiles with RDD calculated by drift-diffusion simulation. The TAT current is calculated based on SRH model. The trap energy level is fixed to be mid-gap in order to evaluate the fluctuation of maximum TAT current due to RDD.

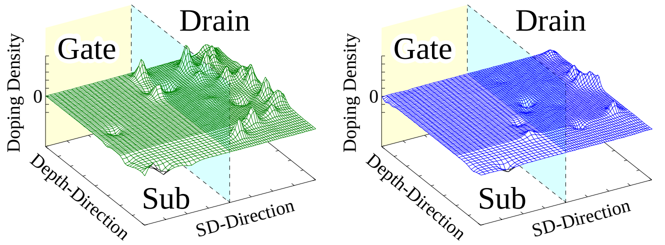


(a) Potential profile (b) Deffinition of ΔV_{QM}

Fig. 3: Analytical effective potential model[6], $V_{eff}(r)$, is used as the discrete dopant potential. (a) The cut-off radius r_c of $V_{eff}(r)$ is calibrated to reproduce a quantum corrected coulomb potential. (b) The quantum corrected potential is defined as the potential with which the quantum electron density (calculated by solving Schoredinger equation) is obtained based on classical density of states. The discrete dopant potential is converted to the doping density profile to include into drift-diffusion simulation.



(a) Surface electric field profiles. (b) Doping density of dev.A.



(c) Doping density of dev.B. (d) Doping density of dev.C.

Fig. 4: (a) Electric field profiles along source-drain direction at the substrate surface for devices with different RDD profiles. (b) Doping density profile of dev.A, which shows strong surface electric field. Compared with doping profiles of other devices ((b) dev.B with medium electric field, (c) dev.C with low electric field), dev.A has more discrete donors in the channel region which causes large potential difference between channel and gate electrode. Large TAT current fluctuation can be caused by such electric field difference if discrete traps are located around the regions.

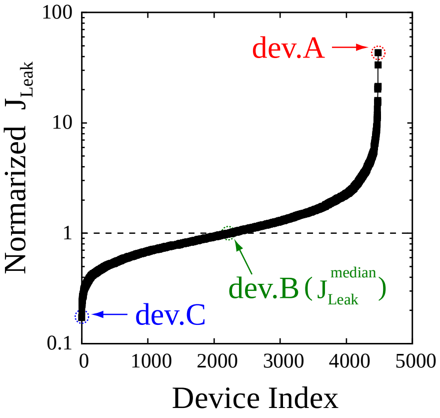


Fig. 5: The maximum junction leakage current within each device profile, J_{Leak}. J_{Leak} is normalized by median J_{Leak} (J_{Leak}^{median}) and plotted in ascending order. J_{Leak} is strongly affected by electric field fluctuation and enhanced to about 2 orders larger magnitude than the median device.