Dopant-Assisted Tunnel-Current Enhancement in Two-Dimensional Esaki Diodes

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Abstract — **We study ultrathin (2D) lateral Si Esaki tunneling diodes, and find that anomalous current peaks and humps are observed to be superimposed on the ordinary negative differential conductance (NDC). The remarkable enhancement of interband tunneling current is primarily ascribed to resonant tunneling via gap-states created by large potential fluctuation due to prominent inhomogeneity of dopant distribution (dopant-clusters) in the 2D depletion region.**

1. Introduction

Recently, interband tunneling originated in Esaki tunnel diodes [1,2] has attracted increasing interest for low power consumption devices. In fact, tunnel field-effect transistors (TFETs) [3] use interband tunneling to achieve steep sub-threshold slopes. However, since tunneling current is relatively low in Si because of indirect bandgap nature, a number of ways to enhance the current are proposed by involving hetero-structures [4], deep-level impurities or isoelectronic traps [5].

In this paper, we find that interband tunneling current is strongly enhanced in ultrathin (2D) tunnel diodes without introducing extrinsic impurities. This remarkable current enhancement is ascribed to the resonance via dopant-clusters formed due to the 2D-characteristic inhomogeneity of dopant distribution.

2. 2D Esaki tunneling diodes

We fabricated Esaki tunneling diodes in silicon-on-insulator (SOI) layers. The *pn* junction is formed in a constriction region, with a final width on the order of ~100 nm and thickness ~5 nm, as shown in **Fig. 1(a)**. The conventional selective-doping processes were used to define the *n*-type region (doped with phosphorus, P, $N_D \approx 2.7 \times 10^{20}$ cm^{-3}) and the *p*-type region (doped with boron, B, $N_A \approx 0.9 \times 10^{20}$ cm^{-3}) with an overlap area. Doping profile is shown in **Fig. 1(b)**.

3. Low-temperature *I-V* characteristics

I-V characteristics measured in forward bias regime at T=5.5 K are shown in **Fig. 2(a)**. It is seen that current rapidly increases with increasing V. In the low voltage region (<0.25 V), however, several specific features can be noticed, as marked in **Fig. 2(b)**. First, fine current humps at ~20 and ~60 mV are observed, which are due to phonon-assisted interband tunneling [6], in addition to well-known negative differential conductance (NDC) due to interband tunneling current [1,2]. Secondly, we find two extra features, i.e., the enhanced-current peak (A) and hump (B). Such interesting features are often observed in our 2D diodes, although the current peak and hump structures are different from each other.

4. Analysis of enhanced-current features

In early work on Esaki diodes [7], excess current, which is observed in higher voltage region than the interband tunneling peak voltage (~0.1V), is ascribed primarily to a two-step process, i.e., tunneling and recombination (SRH mechanism) involving a gap-state. The hump (B), which also lies in the excess current region, is likely to be caused by tunneling-recombination process [**Fig. 2(d)**]. In contrast, since the narrow peak (A) appears at $V \approx 0.1$ V superimposed on the interband tunneling peak, the peak (A) is ascribed to resonant tunneling through an aligned energy gap-state without energy dissipation [**Fig. 2(c)**].

In order to confirm this model, we studied the substrate bias (V_{sub}) dependence of the current peak, as shown in **Fig. 3**. V_{sub} is expected to work to shift the gap-state energies present in the depletion region. The features A and B significantly depend on V_{sub}, while other regions are insensitive to V_{sub}. It is found that the behaviors of A and B are different and shift oppositely as a function of V_{sub} (see **Fig. 4(c)**). The difference is consistently explained by the spatial locations of the gap states relative to the density of states (DOS) in the leads, as schematically illustrated in **Figs. 4(a)** and **4(b)**.

Finally, we studied the origin of the gap-states by simulation and conclude that the energy states are ascribed to potential fluctuation produced by localized dopant clusters, as schematically shown in **Fig. 5(a)**. Such large potential fluctuation is generated especially for 2D systems, but is significantly screened for 3D systems. Simulated potential profiles for the ultrathin co-doped *pn* junction, as shown in **Fig. 5(b)**, confirm the presence of huge potential fluctuation. The simulation results are quite consistent with our model.

5. Conclusions

We studied ultrathin Esaki diodes fabricated in silicon-on-insulator layers. We find interband tunneling current with strong enhancement due to energy states in the depletion region. These states are ascribed to localized dopant clusters that prominently appear in two-dimensional structures. These findings give an insight into the impact of low-dimensionality on the operation of interband tunneling devices.

Acknowledgements

This work was supported by MEXT Kakenhi (23226009, 25630144) & Coop. Res. Project (RIE, Shizuoka Univ.).

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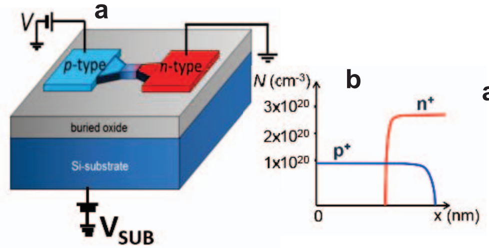
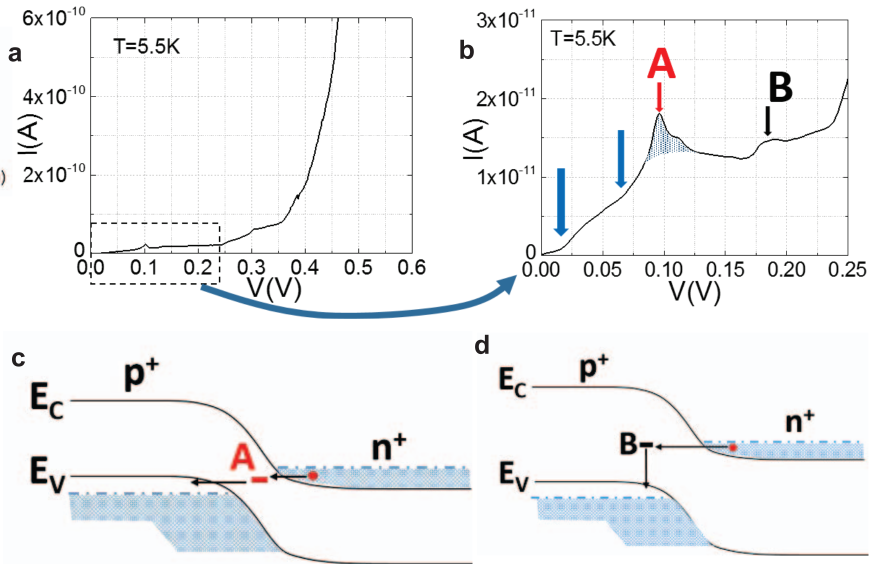


Fig. 1. (a) Schematic structure of nanoscale lateral *pn* junctions and *I-V* measurement circuit. (b) Doping profile across the junction area.



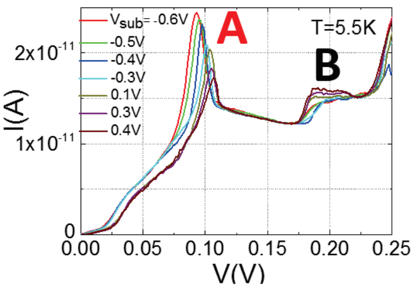


Fig. 3. *I-V* characteristics as a function of V_{sub}, showing the evolution of features A and B.

Fig. 2. (a) Low temperature (5.5 K) *I-V* characteristics in forward bias region in a wider voltage range. (b) Zoom-in on the low bias region, with marks indicating main features (including peak A and hump B). (c)-(d) Band diagrams schematically showing energy states responsible for features A and B.

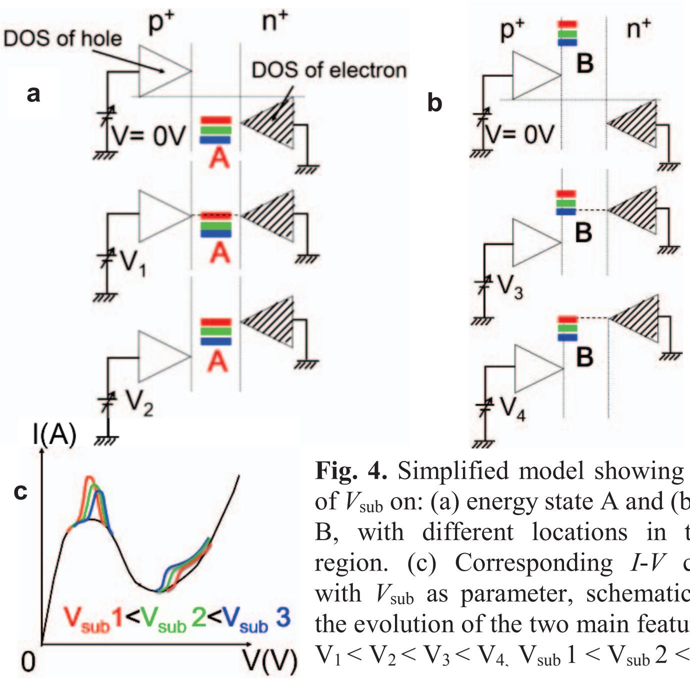
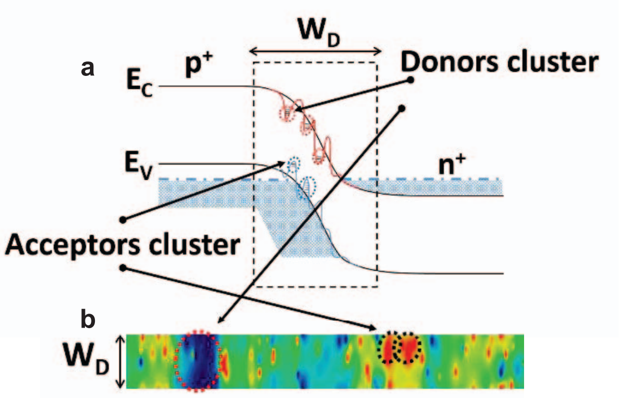


Fig. 4. Simplified model showing the influence of V_{sub} on: (a) energy state A and (b) energy state B, with different locations in the depletion region. (c) Corresponding *I-V* characteristics with V_{sub} as parameter, schematically showing the evolution of the two main features. Here, $0 < V_1 < V_2 < V_3 < V_4$, $V_{sub}1 < V_{sub}2 < V_{sub}3$.



P-B co-doped 2D depletion

Fig. 5. (a) Schematic band diagram of a heavily-doped *pn* diode, with clusters of dopants in the depletion region. (b) Simulation of co-doped 2D depletion region, showing possible formation of dopant clusters.