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Single Donor Transistors with Nanochannels and Role of Dielectric Confinement

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ABSTRACT We have studied Single donor transistors with designed nanochannels in which the tunnel barrier height is enhanced due to dielectric confinement. For single electron tunneling effects the charging energy is significantly large. Which is a first limiting factor for shallow dopants? At high temperatures, thermally activated transport became quickly dominant. We have found that at high temperature operation of electron tunneling occurred via a single donor. We have found that the single dopant devices operating at room temperature paving the way for practical applications based on individual dopant atom in silicon nanodevices. We have also found that in nanopatterned channel transistors, single electron tunneling via individual positive donors was observed at elevated temperatures. The obtained results were found in good agreement with previously obtained results.

KEYWORDS Donor, Nanochannels, Barrier Height, Dielectric Confinement, Tunneling, Dominant, Dopant.

INTRODUCTION

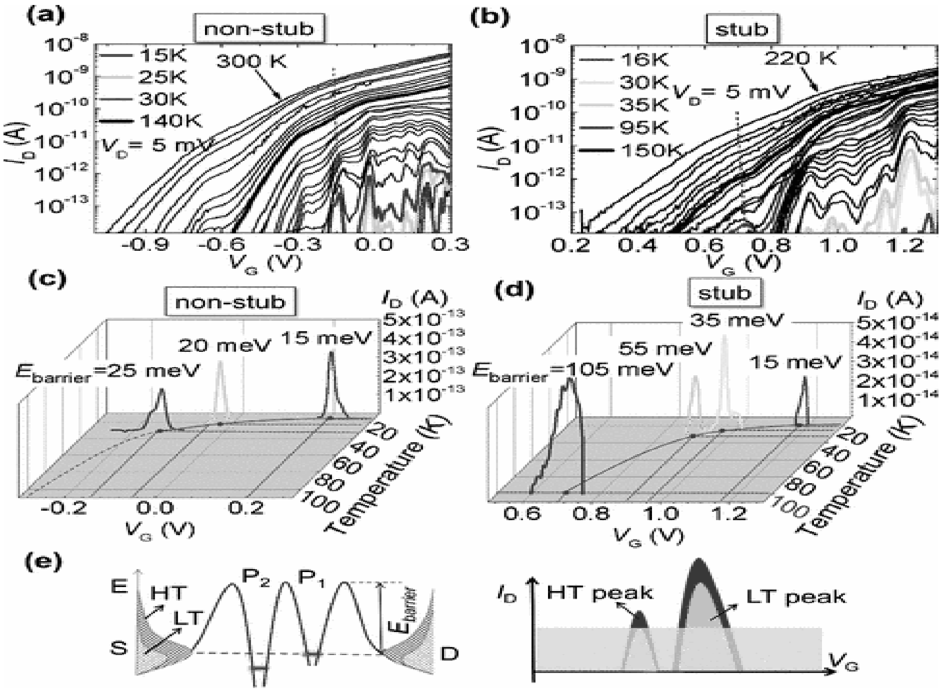
Silicon technology allow electrical measurements of electron or hole tunneling through individual dopants in the channel of silicon transistors[1-4]. The obtained results were for transistors having channels without any special patters[5-6]. In these studies dopants maintain their shallow ground states and tunneling transport only for low temperatures. In most reports on single dopant devices, the target application is quantum computing[7] for which low temperatures are suitable because of a longer coherence time. The tunneling operation via-dopants at elevated temperatures are lacking and for application towards complementary metal oxide semiconductor based electronics, and a higher tunneling operation temperature is crucial. In silicon nanoscale devices dopant atoms gain are active in the transport characteristics[8-9]. Dopants have an essential role as a free carrier sources because of their shallow energy levels[10]. Ligowski etal[11] and Anwar etal[12] studied that while the surface topolography was maintained flat the Kelvin probe force microscopic measurements at low temperature revealed potential fluctuations consistent with the characteristics of individual ionized donors. Moraru etal[13] observed sharp and irregular coulomb oscillations for doped channel device consistent with their previous results.

METHOD

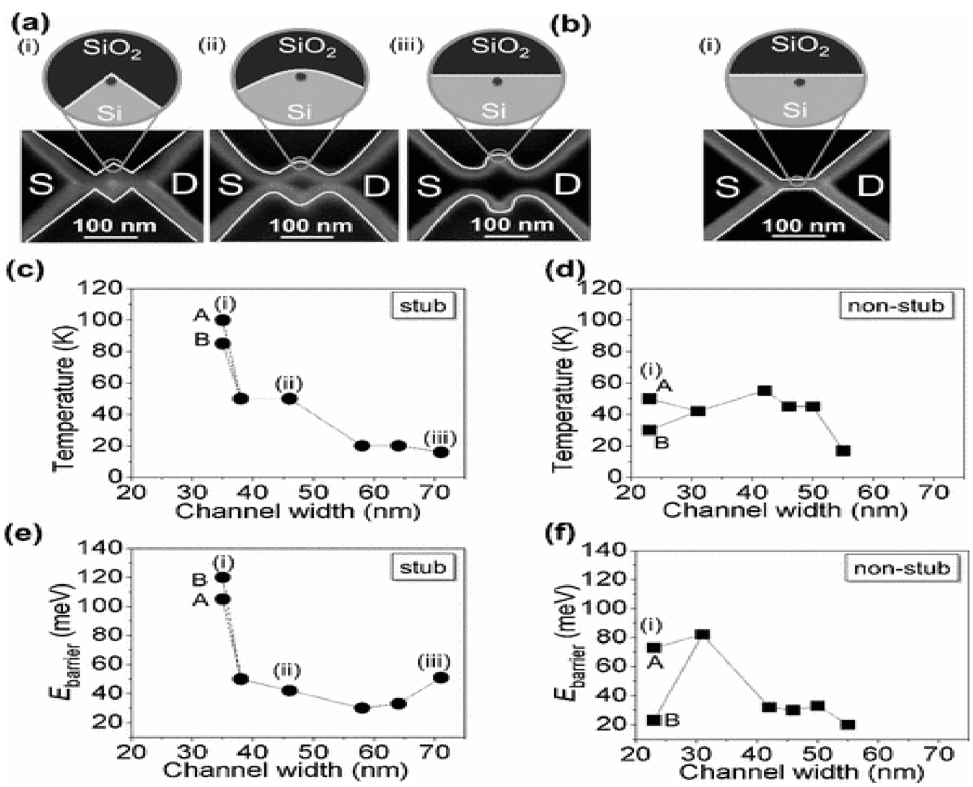
We have considered two types of devices (i) without and (ii) with a stub structure in the centre. In stud-channel transistors a donor located within the stub region experiences a strong dielectric confinement effect because it is mostly surrounded by S_iO_2. For the case of non stub field effect transistors unlike stages are found. This result in deepening of donor ground state promotes electron tunneling operation even at elevated temperatures. The top silicon layer was made of n type doped by thermal diffusion with phosphorous to a concentration $N_D \cong 1\times10^{18} cm^{-3}$, corresponding to an average distance between neighboring p donor atoms of ~10 nm. The top silicon layer was surrounded by a thermally grown 14 nm thick S_iO_2 layer before Aluminium deposition for electrical contacts. For non stub and stub channel field effect transistors $I_D - V_G$ Characteristics were measured at a small source drain voltage V_D. The temperature was changed as a parameter from ~ 15 to 300 k. The obtained results were compared with previously obtained results.

RESULTS AND DISCUSSION

$I_D - V_G$ Characteristics are shown in graph (1) which is plotted in the V_G temperature plane. The peaks successively appear with increasing temperature and ascribed to tunneling via positive donors with deeper ground state energies. The current peaks of deep donors are not observed at low temperatures because tunneling rate is too small due to the high potential barriers. Graph (1) also shows that with increasing temperature due to broadening of the Fermi-Dirac electron distribution in the reservoir the tunneling rate is enhanced and the corresponding current peaks successively emerge, exceeding the detectable current level. It was found that for the stub channel field effect transistor, the last emerging current peak appeared at $T \cong 100K$, which is the highest temperature reported so far for single dopant transistors operating in the single electron tunneling mode. Graph (2) shows the plot only for highest temperatures corresponding to the last emerging current peaks for sub channel field effect transistors as a function of channel width. It was found that with decreasing width the highest operation temperature systematically increased. For the narrowest sub channel devices, it was confirmed by two devices. This is due to high temperature and an enhanced tunnel barrier height compared to bulk donors, which allowed the efficient suppression of thermally activated transport even at such elevated temperatures. According to the dielectric confinement effect the last emerging peaks corresponded to positive donors near the edge of the stub structure because screening of the donor potential is determined by the surrounding S_iO_2.



Graph 1: Temperature dependence of $I_D - V_G$ characteristic $\left(V_D = 5\,\mathrm{mV}\right)$ for the smallest devices with a (a) non-stub channels (15-300 K) and (b) stub channel (16-220 K).



Graph 2: SEM images of devices channels with different patterns.

CONCLUSION

We have studied single donor transistors with specially nanochannels in which the tunnel barrier height was enhanced due to dielectric confinement. It was found that at high temperatures thermally activated transport became quickly dominant. A single donor works as an atomic quantum dot mediating single electron tunneling transport from source to drain. For higher temperature single electron tunneling operation, the donor's tunnel barriers must be considerably higher. We have used a special design of a nanoscale silicon channel with a central stub region in which a phosphorous donor's ground state became deeper due to the dielectric confinement effect. The obtained results were found in good agreement with previously obtained results of theoretical and experimental works.

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