Single dopant implantation into a nanoscale MOSFET devices

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Classical metal-oxide-semiconductor field effect transistors (MOSFETs) produced by industrial fabrication methods are now sufficiently small that random variations in the number and placement of donors in ultra- scaled transistors result in inconsistent behavior. This is already a major issue in the microelectronics industry for devices operating at room temperature.[1] Further, the Bohr radius of a donor electron is now a significant fraction of the size of the device.[2] This has opened the possibility of new quantum mechanical dependent functionalities observed with adventitiously doped devices at 4 K.[2–4] Emerging deterministic doping technologies aim to mitigate statistical fluctuations in the doping of these devices while also providing significant potential for solid- state quantum computers.[5–8]

Low energy single dopant implantation into micron-scale devices has been reported by two groups.[9,10] Further, time-resolved control and transfer of a single electron between two deterministically implanted P atoms in a micron-scale device has been successfully demonstrated.[11] Deterministic doping schemes which employ ion implantation are based on ion impact signals from electron-hole (e − h) pairs,[9,12] secondary electrons[13,14] or modulation of the drain current, Id.[10,15,16] For the latter, discrete downward steps in Id have been observed with low energy Si implantation into a micron scale SOI wire.[16] However, other reports show discrete upward steps in I_d have been observed in micron-scale MOSFETs.[10,15] By an appropriate choice of ion and implant energy we can selectively induce discrete upward or downward steps in I_d to elucidate the mechanisms involved in these opposing responses in nano-scale MOSFETs. The full potential of new single-atom functionalities requires nano-scale devices and multi-gate silicon-on- insulator (SOI) transistors are promising architectures.[17] In these devices, Id modulation induced by ion impact arises from both electronic and nuclear stopping processes in which ionisation and Frenkel pair production, respectively, are the major effects.

Here we examine the Id modulation in a nano-scale SOI MOSFET from the passage through the channel of 500 keV He^+ ions for which electronic stopping is the dominant mechanism for dissipation of the kinetic energy. We contrast this with the modulation induced by 14 keV P^+ dopants which mainly stop in the channel and for which nuclear stopping is dominant. In the latter case this modulation is the deterministic signal where precision placement is optimized by using a specialized gate structure which also acts as a surface mask. The placement of P donors in MOSFET devices using an integrated PiN device is also discussed.

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