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Interplay between Mutual Capacitive Coupling and Tunneling in Silicon Single Electron Transistor Coupled to Dopant Atom

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ABSTRACT We have studied mutual capacitive coupling and tunneling in the silicon single electron transistor coupled to a dopant atom. We observed a spectacular enhancement of the conductance through the single electron transistor when transport occurs by resonant tunneling via the dopanant atom. We found that in certain range of temperature the mesocopic fluctuations of coulomb blockade peaks are suppressed. The coulomb blockade have equal height which is determined by the transparencies of the single electron transistor tuned barriers and it is independent of the electron motion inside the single electron transistor island. The peak height remains constant over a large number of coulomb blockade oscillations and varies weakly with the gate voltage due to the way the gate couples to the single electron transistor tunnel barriers. A strong modulation of the peak height on a scale of several coulomb balckade osciallations was considered. In silicon nanostructures based on doping modulation charge traps occur naturally at the borders of the doped regions, where the dopants are likely to diffuse away from their majority distribution and from nearly isolated charge traps. We have studied the effects associated with a single charge trap in the coulomb blocade oscillations of single electron trap. Our results are used to assess the feasibility of using single electron transistor as a means to manipulate and readout single dopant atoms in silicon. We found that at low temperatures the linear conductance can be derived from a circuit approach in which the donar single electron transistor system is replaced by a circuit of resistors. Capative and tunneling coupling were found resulting an increase of the conductance through the single electron transistor by up to one order of magnitude. The obtained results were compared with previous obtained results and were found in good agreement.

KEYWORDS Interplay, mutual capacitive, coupling, tunneling, fluctuation, blockade.

INTRODUCTION

The use of a single electron transistor for the quantum mechanical measurement of the dopant qubit requires characterization of the coupling strength between the single electron transistor and the dopant atom. Single dopants in silicon have emerged as promising studies for qubits of the small size[1] silicon technology offers the opportunity to realize classical single electron transistors[2-6] and to probe single dopants[7-9]. The interplay between coulomb interaction and tunneling studied in mesoscopic physics[10], where it leaded to the coulomb blackode oscillations[11-12] of conductance and observed in metallic single electron transistors[13] and semi conductor quantum dots[14]. The energy scale governing the coulomb blackode oscillations in a metallic single electron transistor is set by the charging energy $E_c = \frac{e^2}{2C}$ where C is the total capacitance of the single electron transistor island relative to the surrounding conductors and –*e* is the electron charge. At temperatures $T \sim E_C$ the conductance as a function of the gate voltage acquires an oscillatory component and as the temperature is decreased, it turns into a series of spikes at $T \sim E_C$. Metallic single electron transistors have found several applications including charge detectors and amplifiers[15-16], electron pumps for metrology[17-18] and low temperature thermometers[19]. At the lowest temperatures the height of a coulomb blockade peak depends on the properties of the electron wave function inside the single electron transistor. The existence of the temperature regime ΔE = $T \sim E_C$ makes single electron transistors outstanding for applications. We have studied the mutual capacitive and tunneling coupling between a dopant atom and a single electron transistor realized in a silicon nanowire field effect transistor.

METHOD

We have developed a theory that takes into account for tunneling and capacitive coupling between dopant atom and single electron transistor and assessed the coupling strengths by analyzing the coulomb blockade oscillations of the linear conductance. We have formulated a simple electrostatic model that helps in explanation of results. We have proceeded with a systematic analysis of the electrostatic model. We have considered the low temperature limit in which transport is additional and governed by the spectrum derived from the electrostatic model. We have completed the electrostatic model by Kinetic energy and tunneling terms and proceeded with the study transport through the coupled donor single electron transistor system by means of rate equations. The linear conductance was derived from a circuit approach in which the donor single electron transistor system is replaced by a circuit of resistors. We have analysed the validity of this approximation at higher temperature by solving the rate equations numerically and found agreement for the parameters sets that extracted from fitting to the experimental data. The system of a coupled dopant atom and single electron transistor have used for readout of the single dopant atom.

RESULTS AND DISCUSSION

Figure 1 shows the tunneling coupling of an *As* atom to the lead and single electron transistor island, resonant features are found in the linear and differential conductance. Figure 2 also shows the results of our work. We have formulated a simple model for the electrostatic energy of the device and explained the observed behavior in terms of sequential tunneling of electrons between energetically state. The dopant atom resides in one of the single electron transistor barriers. The energy associated with the charges in the device depends on the donor charge $n = 0,1$ and the single electron transistor charge N can be written as $E(n,N) = \in_d n + E_C (N - N_g)^2 + U_{12} n (N - N_g)$ where $\in_d$ is the energy of the donor level, E_C is the charging energy of the single electron transistor, $N_g = \frac{C_g V_g}{e}$ is the dimensionless gate voltage, C_g being the gate to single electron transistor capacitance and U_{12} is the energy of mutual capacitive coupling. The top gate couples the single electron transistor and the donor. The lever arm of the donor is smaller than that of the single electron transistor. This is expressed by the relation $\in_d = -\alpha E_C N_g + \text{constant}$, where α = 1. At low temperatures transport occurs due to transition from the ground state to the lowest in energy charge configurations. The stability diagram commonly used for double dots shows the ground state as a function of $\in_d$ and N_g. The activation energy was determined by the difference $E(n,N) - E(n,N+1)$. Both terms were determined at the same n, which corresponded to the condition that there is no current through the donor. The energy difference reaches zero every time the working line of the device intersects a vertical line of the stability diagram, which is possible for $N_g < N_g^-$ and $N_g > N_g^+$. At low temperatures $T \sim E_C$, the conductance is express by

$$G(N_g) = \sum_N \left[(1 - \langle n \rangle) G(x - x_N) + \langle n \rangle G\left(x - x_N - \frac{U_{12}}{T} \right) \right].$$

where $\langle n \rangle$ is the average occupation of the donor. We have separated the effect of tunneling through the donor form direct tunneling by setting $g_L = 0$. By lowering the temperature, the single electron transistor conductance due to sequential tunneling is suppressed as

$$G \propto \exp\left(\frac{-\Delta}{T} \right)$$

Where Δ is an activation energy and T is the temperature. The activation energy around a sequential tunneling peak is given by $\Delta = | \; |E(n,N) - E(n,N+1)$; because the transport occurs due to the fluctuation $N \leftrightarrow N+1$ at fixed $n = 0$ at $N_g < N_g^-$ or $n = 1$ at $N_g > N_g^+$. We have completed the electrostatic model with kinetic energy and tunneling terms and gave a rate equation description of the transport problem. We have analysed different temperature regimes and found at T = U_{12}, the rate equation description is identical to a description in which the actual interacting system is replaced by a circuit of resistors. In order to calculated the linear conductance in second quantization form and complemented it with tunneling terms. The donor Hamiltonian takes the form

$$H_d = \in_d \sum_{\sigma \uparrow, \downarrow} d_\sigma^\dagger d_\sigma + U_\infty n_\uparrow n_\downarrow,$$

where $d_\sigma^\dagger d_\sigma$ is the creation (annihilation) operator of an electron of spin $\sigma = \{\uparrow, \downarrow\}$ on donor. The donor occupation is given by $n = n_\uparrow + n_\downarrow$, where $n_\sigma = d_\sigma^\dagger d_\sigma$ is the occupation of one spin species. The onsite repulsion energy U_∞ on the donor is assumed to be large enough to exclude the occupation $n = 2$. The electrostatic and tunneling coupling between donor and single electron transistor island is given by

$$H_{dD} = U_{12}(N - N_g) \sum_\sigma n_\sigma + t_{12} \sum_{k\sigma} \left(d_\sigma^\dagger f_{k\sigma} + H.c. \right).$$

where t_{12} is the tunneling amplitude between the donor and single electron transistor. This leaded i.e., the source L and the drain R are described by

$$H_{leads} = \sum_{l=L,R} \sum_{p\sigma} \xi_p c_{lp\sigma}^\dagger c_{lp\sigma}$$

where ξ_p is the dispersion relation in the leads and $c^{\dagger}_{lp\sigma}\left(c_{lp\sigma}\right)$ is the creation operator of an electron with momentum p and spin σ in lead $l = L;R$. The tunneling between the donor and left lead is described by

$$H_{dL} = t_L \sum_{p\sigma} \left(d^{\dagger}_{\sigma} c_{Lp\sigma} + H.C. \right)$$

Where t_L is the corresponding tunneling amplitude. The tunneling between the single electron transistor island and the leads is described by

$$H_{DLR} = \sum_{l} V_l \sum_{kp\sigma} \left(f^{\dagger}_{k\sigma} c_{lp\sigma} + H.c. \right)$$

Where V_l is the tunneling between the single electron transistor island and the lead $l = L,R$.

We have evaluated the conductance exactly i.e. dots by solving the Pauli master equation numerically. We have found good agreement between the two approaches for the parameters relevant to the experiment.

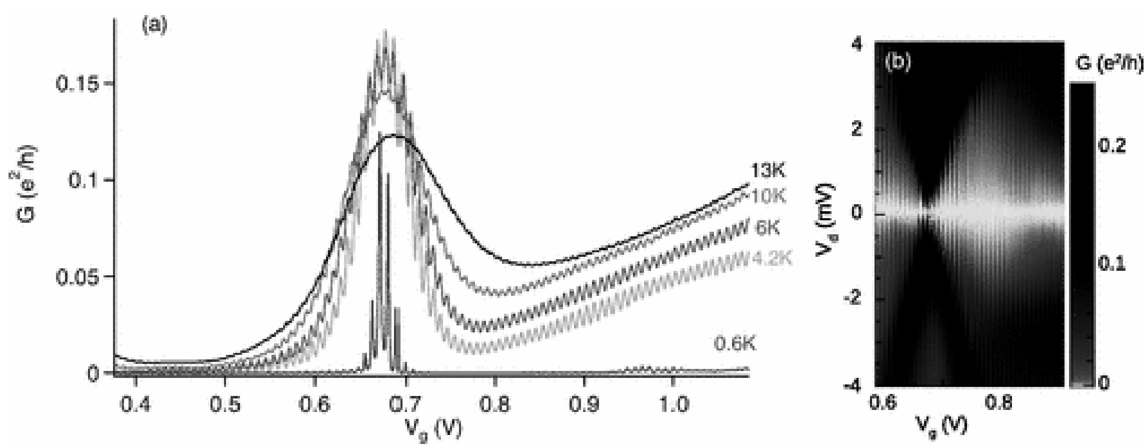

Figure 1: Linear conductance through the silicon nanowire as a function of the gate voltage V_g at various temperatures. The strong, resonance-like modulation of the Coulomb blockade oscillations is attributed to the presence of a dopant atom in the Single-electron transistor barrier.

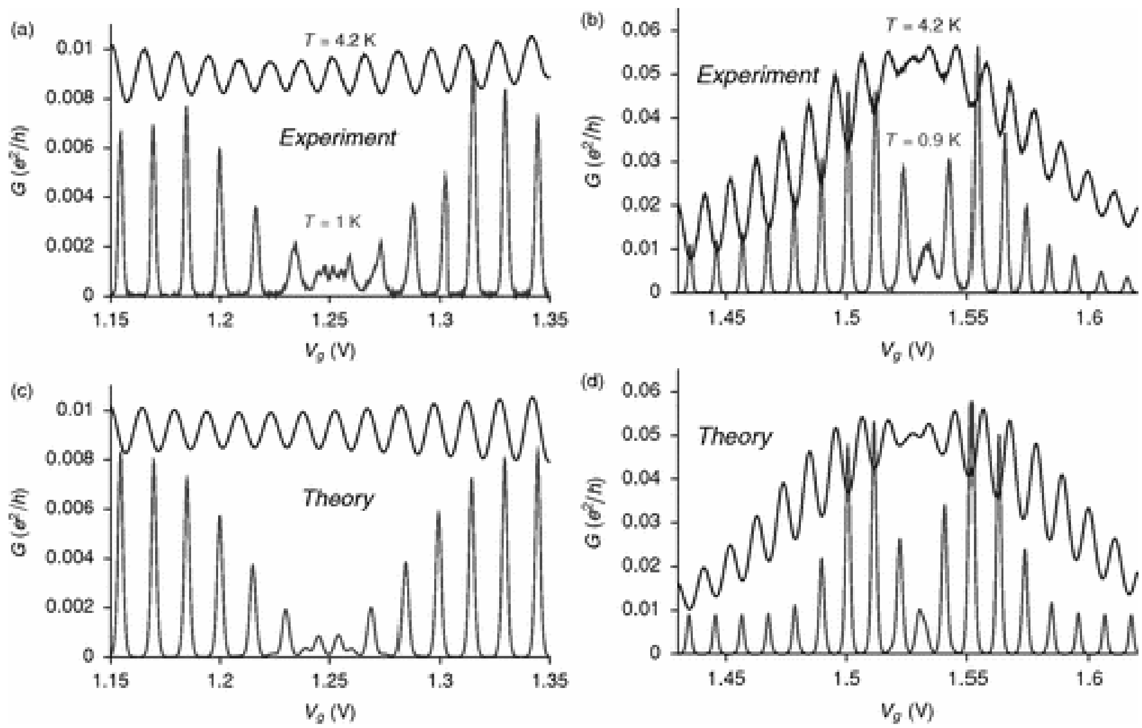

Figure 2: Linear conductance in which the dopant atom couples mostly capacitively to the Single-electron transistor. At $T = 1K$, the Coulomb blockade peaks are suppressed in an interval of V_g, marking the extension of the anomaly. At $T = 4.2K$, the Coulomb blockade oscillations are weakly modulated.

CONCLUSION

We have studied the mutual capacitive and tunnel couplings between a dopant atom and a single electron transistor realized in a silicon nanowire field effect transistor. We have found interplay between mutual capacitive coupling and tunneling in the silicon single electron transistor coupled to a dopant atom. We have found that in silicon nanostructures based on doping modulation the charge traps occurred at the borders of the doped regions, where the dopants diffuse away from their majority distribution and form nearly isolated charge traps. We have also found the effects associated with a single charge trap of dopant atom in the coulomb blockade oscillations of a single electron transistor. We found that at low temperatures the linear conductance be derived from a circuit approach in which the donor single electron transistor system is replaced by a circuit of resistors. We also analysed the validity of this approximation at higher temperature by solving the rate equations numerically and found in good agreement for the parameter sets. The obtained results were compared with previously obtained results of theoretical and experimental works and were found in good agreement.

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