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To cite this article: Morteza Erfani et al 2009 J. Phys.: Conf. Ser. 193 012048

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Multiple microwave resonance interaction in silicon single-electron transistors

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Abstract. Silicon single-electron transistors are promising nanodevices for implementation of quantum logic gates. Single frequency continuous wave microwave spectroscopy, carried out under cryogenic conditions on dc biased degenerately doped transistors have previously shown many high quality factor resonances in the drain current modulation, indicating the presence of long-lived excitations. However, such measurements are unable to indicate coupled behaviour between the systems undergoing resonance. Coupled behaviour is a necessary precursor for quantum gate operation. In this work, we investigate the response of devices to two frequency continuous wave microwave spectroscopy, which is a potential method for induced coupling.

1. Introduction
It is well-known that the source-drain current of a dc biased degenerately doped single electron transistor (SET) can be influenced by microwave irradiation [1]. Continuous wave (CW) microwave spectroscopy at liquid helium temperature shows a large number of resonances with quality factors (Q-values) up to $\sim 10^5$, which are thought to result from resonantly driven electrons tunnelling between sites where the electron is localised by the donor distribution. Equivalent experiments on conventional silicon MOSFETs do not show these large number of high Q-value resonances [2, 3]. The displacement of the tunnelling electron in the silicon SET modifies the electrostatic environment inside the SET island which changes the magnitude of the tunnel barriers to the source and drain leads. This change in the tunnel barrier transmission results in an increase or decrease of the SET current at resonance, despite the fixed bias condition. A typical high quality factor of $10^5$ at 1 GHz indicates an energy relaxation time of $10 \mu$s, suggesting that this driven electron tunnelling mechanism is well isolated from the environment. The quantum mechanical nature of these resonances is indicated by their very large number ($\gg 10^4$ in the range of 1 - 10 GHz) and their very high Q-values (see figure 1).

2. Single frequency microwave spectroscopy
In the CW microwave spectroscopy, the resonance frequency of a peak gives the energy splitting for the electron occupying the donor sites involved in the tunneling event. Also the Q-value of each resonance indicates the relaxation time in the absence of inhomogeneous broadening and characterises the energy loss of the system. To investigate the coherent dynamics of a resonance,
Figure 1. (a) Wideband monochromatic CW microwave spectroscopy showing the large number of resonances in the range from 2 - 3 GHz. The inset shows a resonance (indicated by the arrow) with the Q-value of $\sim 10^5$ in a view expanded by 1000 times. (b) Cross-sectional schematic view of the microwave coupling scheme. (c) SEM image of a typical device. (d) Schematic cross-section of the material structure.

Pulsed excitation of the system is needed. Rabi oscillations have previously been observed in CW-pulsed spectroscopy, giving a timescale for the rate and duration of coherent processes [4]. A Rabi frequency ($\Omega$) of $\sim 1$ MHz was observed for resonances in the frequency range ($\omega$) of a few GHz, so that the condition $\hbar \Omega \ll \hbar \omega$ ensures suppression of the fluctuation of electron occupation numbers for the localised sites. Each resonance can be treated as a separate qubit in a Hilbert space characterised by a spatial Rabi oscillation of an electron between the pair of localised states. To extract qubit information, necessary for a computational process, the change in SET current must be detected in response to one or more additional microwave pulses.

3. Two frequency microwave spectroscopy

In practice, quantum information processing requires controlled quantum coherent coupling between qubits to enable gate operation [5]. Coupling may be demonstrated by 2-D CW microwave spectroscopy. Previously, both direct and indirect methods for the coupling of microwave radiation to a nanodevice have been used in 1-D CW and pulsed-CW microwave spectroscopy. In this work, microwave signals were supplied successively by these two techniques to the same device. It was shown that resonances mostly appeared at the same frequency, but were modified in shape and amplitude. The indirect microwave coupling method uses a polished end of a semi-rigid coaxial cable, terminated $\sim 0.5$ mm away from the nano-device to provide impedance matching. The directly coupled microwave signal is capacitively connected to the source-drain leads of the SET. This is more efficient than the indirect method but leads to a greater electrical noise in the nano-device. The strength of coupling between the microwave field and the system undergoing spatial Rabi oscillations depends on their relative direction. The electric field directions in the nano-device due to the directly coupled and indirectly coupled microwave signals are mutually perpendicular. Therefore, the same CW spectroscopy measurement may look different in the two coupling methods.

We report on experimental measurements at a temperature of 4 K on a SET with a doping
concentration of $N_D = 3 \times 10^{19}$ cm$^{-3}$. In a frequency range of 4.4 MHz centred at 2.24 GHz, there are 4 high Q-value resonances. An indirectly coupled microwave signal was swept over this range. Another fixed frequency signal was directly coupled and stepped for each sweep of the indirectly coupled microwave signal over part of the same frequency range. The two sources were independent i.e. phase locking was not used. The same measurement was repeated for different power outputs on the direct and indirect coupling. The results for this measurement are shown in the grey scale map in figure 2. Displacement of electrons within the SET, say due to a change in the gate voltage, is known to cause small shifts in the resonant frequencies. This is seen as a slope on the trajectory of a resonant feature with respect to the swept $x$-axis (the indirectly coupled signal). The trajectories show different characteristic behaviours in different powers. The peak amplitude associated to each trajectory alters with power. This effect is so strong on two of the resonances such that they have too low amplitudes to be detected at certain power combinations. The centre frequencies of these resonances are at around 2.2391 and 2.2415 GHz which are indicated by two arrows in figure 2. Also, the slope of the trajectory varies with power. At certain power combinations some resonances show anticrossing behaviour, most noticeably at the centre of the resonance is shown in figure 3 in an expanded view. A sharp resonance is also detectable on the vertical axis. The centre frequency of this resonance shows a strong dependency on the combination of the two power outputs. It starts from 2.2409 GHz at 0 dBm for both signals and increases by increasing the indirect power up to +10 dBm. It then passes out of the frequency range at +15 dBm. This peak appears back on the frequency range by increasing the direct power to +5 dBm and again shifts upwards with increasing indirect power.

The dependency of a resonance frequency both on power and frequency of a second microwave signal, indicates an energy exchange mechanism inside the nano-device caused by the two frequencies. This can be a useful phenomenon for the purpose of conditional gate operation, as the resonance condition of the excitation depends on a second signal. In addition, the anticrossing behaviour observed under certain conditions suggests a coherent interaction between two systems undergoing simple harmonic motion. These two systems must be located within the transistor structure and can be manipulated rapidly in the time domain by the application of pulsed microwave signals at frequencies designed to select specific resonances. Such an approach to selective manipulations can be faster and more highly selective than one based on changing gate voltages.
Figure 3. Two frequency spectroscopy for an indirectly coupled microwave signal (+15 dBm horizontal axis) and a directly coupled microwave signal (+5 dBm vertical axis) showing an anticrossing behaviour.

4. Conclusion and future work

In previous works, degenerately doped silicon SETs have been widely investigated as the basis for single electron memory and classical logic applications [6–10]. For these purposes, the quantization of the electronic charge and the ability to sense and manipulate charge at the single electron level, were the main technology requirements. However, the limited transconductance and power gain, as well as the lack of control of the offset charge were found to be significant limitations. By contrast, in a multi-qubit system based on the large number of microwave resonances in a single SET, the transconductance and power gain are unimportant. In a practical computer device, more than one microwave signal must be applied at the same time (or at least in close temporal proximity) and coupling between qubits must occur (preferably on demand).

Acknowledgments

This work was supported by the Korea Science and Technology Foundation through the Global Partnership Research Program.

References