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Hyperfine-coupling-programming of current through coupled quantum dots with multiple-sweep bias voltage waveforms

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1. Introduction

Current switching and hysteresis due to electron spin–nuclear spin (hyperfine) coupling have been observed in the two-electron (N=2) spin-blockade (SB) regime of coupled quantum dots [1-7]. Hyperfine coupling has played a key role in recent demonstrations of basic qubit operations [8,9]. Quantum memory with nuclear spins has also been has been proposed [10].

Recently, Baugh et al [3] demonstrated a novel scheme for nuclear spin pumping with subsequent readout. Here we expand on this scheme and apply complex multiple-sweep bias voltage waveforms to “program” unique features into the tunneling current which are memorized on a time scale of a few tens of seconds.

2. Experiment

We use a weakly coupled vertical double dot device for our study [1-3]. Figure 1 shows the differential conductance in the bias voltage (V_{sd})- gate voltage (V_g) plane in the vicinity of the N=2 Coulomb blockade (CB) diamond. Immediately to the right is the distinctive chevron-shaped spin-blockade (SB) region [1]. In the absence of a magnetic field, the SB region is “featureless” and it makes no difference whether V_{sd} is swept in one direction or the other [left side from negative to positive V_{sd} (“up-sweep”); right side from positive to negative V_{sd} (“down-sweep)]. However, on application of a magnetic (B-) field, applied parallel to the current (out-of-dot-plane), for B>0.5 T, features with intricate B-field dependence (marked with black triangle in 0.75 T panels) appear inside the N=2 SB region. The appearance of these features strongly depends on the V_{sd} sweep direction. These features grow in strength with B-field but eventually merge with another larger feature (dark step marked by #) moving in from the right and related to a 2p-state [1].

Earlier reported measurements were performed, with an in-dot-plane B-field, by adjusting the gate voltage to be very close to the position (marked by asterisk in Fig. 1) where the N=1 and 2 CB diamonds touch, and then *either* sweeping the B-field up and down at fixed position in the SB regime [2], *or* capturing current-bias voltage traces, at fixed B-field, that cut through the SB regime [3].

There are many outstanding questions related to the hyperfine interaction, e.g., the sensitivity of the effects to dot structural parameters and to the conditions of the measurement. Nonetheless, measurement protocols utilizing hyperfine related effects can be explored for basic memory and even logic operations.

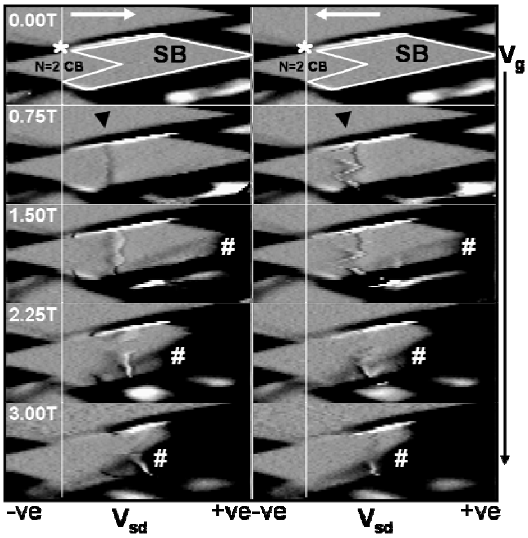

Fig. 1 Differential conductance in the bias voltage-gate voltage plane near the N=2 Coulomb blockade (CB) diamond for the bias voltage swept-up (left side) or swept-down (right side) and for different B-fields from 0 to 3 T. Black, grey, and white respectively correspond to positive, zero, and negative conductance.

3. Bias voltage waveform programming

Reported in Ref. 3, a current step is seen in the SB region at a couple of mV in bias on executing an up-sweep starting from a nuclear spin “relaxed” condition. This step is observed to down-shift by up to ~0.5 mV when read-out on a single following up-sweep after “pumping” the nuclear-spin. We find that additionally the response of the current depends strongly and uniquely, i. not only on applying up-sweeps but also down-sweeps; ii. for waveforms composed of (at least) four sweeps (up or down); and iii. the exact combination of up- and down-sweeps.

Figure 2 shows current- bias voltage traces in the range of -0.5 to 3 mV near the position marked by the asterisk in Fig. 1. Traces grouped into four are for multiple-sweep bias voltage waveforms A-D composed of one down-sweep and three up-sweeps, **and** with the down-sweep (solid) systematically shifted along the waveform from the beginning (A) to the end (D). For example, parts one to four of waveform A are respectively a down-sweep, and three consecutive up-sweeps. Each sweep (up or down) takes ~13.5s, the time between consecutive sweeps is ~7s, any adjustment of bias between consecutive sweeps is done rapidly within ~2s, and the first part of the waveform is proceeded by a ~8s excursion several mV to the left or right of the SB region to "erase" any built-up memory. We stress that away from the V_{sd}-V_g region of interest (but still close to the SB chevron) *either* there is essentially no difference between an up-sweep and down-sweep *or* there is a difference but there is no history dependence.

Likewise, Figure 3 shows current- bias voltage traces in the same bias range again near the position marked by the asterisk in Fig. 1. Traces grouped into four are for multiple-sweep bias voltage waveforms W-Z composed of three down-sweeps and one up-sweep, **and** with the up-sweep (solid) systematically shifted along the waveform from the beginning (W) to the end (Z). For example, parts one to four of waveform W are respectively an up-sweep, and three consecutive down-sweeps. The components of the waveforms are of the same duration as those for the waveforms in Fig. 2.

Inspection of Figs. 2 and 3 reveals the full current response to the eight waveforms A-D and W-Z is distinctively different. Furthermore, representing an up- (down-) sweep with a "0" ("1"), for an in total four part waveform, there are 2^4=16 possible combinations [(0000), (0001), …, (1110), (1111)]. We have measured all these combinations and confirmed the outcome (current response) is different in each case.

3. Conclusions

Applying complex bias voltage waveforms, we can program the current via the hyperfine interaction in coupled quantum dots. We demonstrated the operation of "shifting" a down- (up-) sweep through three up- (down-) sweeps leads to a unique outcome that is memorized in the measured current.

Acknowledgements

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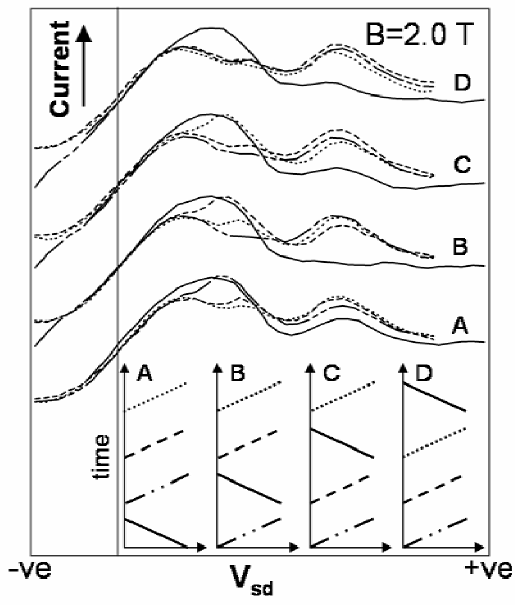

Fig. 2 Current- bias voltage traces at 2.0 T taken near position marked by asterisk in Fig. 1. Traces grouped into four are for bias voltage waveforms A-D composed of one down-sweep and three up-sweeps, **and** with the down-sweep (solid) systematically shifted along the waveform from the beginning (A) to the end (D).

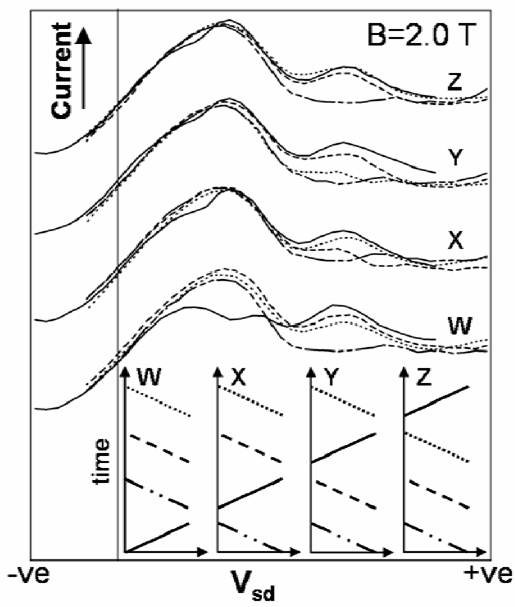

Fig. 3 Current- bias voltage traces at 2.0 T taken near position marked by asterisk in Fig. 1. Traces grouped into four are for bias voltage waveforms W-Z composed of three down-sweeps and one up-sweep, **and** with the up-sweep (solid) systematically shifted along the waveform from the beginning (W) to the end (Z).