Non-invasive charge detection in surface-acoustic-wave-defined dynamic quantum dots.

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Using a non-invasive charge detection method, we detect a flow of electrons trapped in dynamic quantum dots. The dynamic quantum dots are defined by surface acoustic waves (SAWs) and move through a long depleted one-dimensional channel. A one-dimensional constriction is placed next to the SAW channel but in a separate circuit; the current induced by the SAWs through this detector constriction is sensitive to the number of electrons trapped in the SAW minima. We observe steps in the detector acoustoelectric current as the number of electrons carried by SAWs are varied as $1, 2, 3 \ldots$.

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Surface acoustic waves (SAWs) can produce a quantised acoustoelectric current through an empty one-dimensional channel.[1] Electrons are carried through the SAW channel in dynamic quantum dots; on the acoustoelectric current plateau, each dynamic quantum dot contains an integer number of electrons.[2] The fundamental properties of electrons confined to dynamic quantum dots in complex surface acoustic wave circuits have been the object of recent experimental[3,4] and theoretical[5,6] studies. Also, it has been proposed that the spins of single electrons in dynamic quantum dots could be used as qubits for a quantum computer.[7] However, far fewer experimental techniques have been developed for probing the characteristics of dynamic quantum dots, as compared to static dots.[8,9] For static quantum dots, one of the most powerful techniques is non-invasive charge detection:[10] the conduction through a quantum point contact alongside the quantum dot is affected by the charge of electrons in the dot, and this effect has been widely used to probe fundamental quantum properties of confined electrons.[11–16]

Here, we report a non-invasive charge detection measurement in SAW dynamic quantum dots. In our device a detector constriction, which is sensitive to the local electric potential, is created next to a SAW channel. The potential landscape at the detector is partially determined by electrons within dynamic quantum dots in the SAW channel. Therefore the current through the detector constriction senses the charge in the dynamic quantum dots. We describe this technique as *non-invasive* as the occupation state of the dot can be determined without requiring any direct measurement the electron charge or current from the dynamic quantum dot itself.

The device [shown in Figs. 1(a) and (b)] was made using a GaAs/AlGaAs heterostructure which contained a two-dimensional electron gas (2DEG) 97nm below the surface. The 2DEG had a mobility of $160\,\mathrm{m^2/Vs}$ and a carrier density of $1.8 \times 10^{15}\,\mathrm{m^{-2}}$, measured at 1.5 K in the dark. SAWs were generated by applying a resonant microwave signal from an Agilent 8648D signal generator to a transducer, made of 70 pairs of interdigitated fingers with a period of $1\,\mu$m. The microwave signal was pulse-modulated using a Tektronix PG5110 pulse generator with a duty ratio of $10\,\mu\mathrm{s} : 500\,\mu\mathrm{s}$ to prevent heating of the sample by the SAW.[17] The SAWs travelled across the surface of the chip to the NiCr/Au surface gates shown in Fig. 1(b) which were situated 2.5 mm from the transducer. When a negative voltage was applied to the surface gates, the 2DEG below the gates was depleted, creating the SAW and detector channels. +0.3 V was applied to the surface gates during cool-down to minimise random switching noise.[18]

The device operation is shown in Fig. 1(c): the SAW carries electrons into the normally empty SAW channel in dynamic quantum dots. The occupation of each dynamic quantum dot is controlled by the injector gate (G_{Inj})—as the voltage applied to the injector gate (V_{injector}) is swept the acoustoelectric current through the SAW channel (I_{SAW}) takes on quantised values of $I_{\mathrm{SAW}} = nef$ where n is the integer occupation number of electrons in each dynamic quantum dot, e is the electron charge, and f is the frequency of the SAW (typically $\sim 2.7\,\mathrm{GHz}$).[1] The electrons are carried along the channel to the central barrier region by the dynamic quantum dots (the SAW channel gate voltages G_{C1}-G_{C6} have been carefully tuned to avoid any abrupt changes in the gradient of the electric potential, which could otherwise lead to electrons escaping from the dynamic quantum dots[19]). A sufficiently negative bias is applied to the barrier gate (G_B) that no electrons can escape across the barrier between the channels.[3] However, the charge of the electrons in the SAW channel will couple capacitively to the detector channel constriction. Therefore the detector channel

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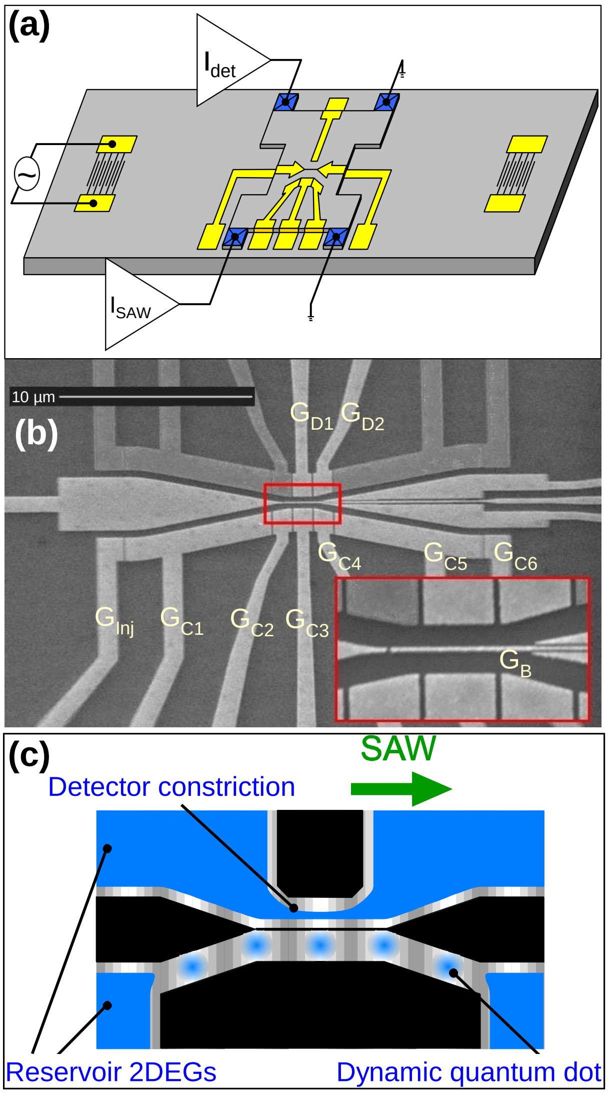

FIG. 1: (colour online). a) Schematic of the device. b) Scanning electron microscope image of the device surface gates. The gates are labeled as follows: detector channel gates (G_{D1} and G_{D2}), barrier gate (G_B), injector gate (G_{Inj}), SAW channel Gates (G_{C1}-G_{C6}). Dark shaded gates were not used in this experiment, and were held at a voltage of +0.3 V (i.e. undefined). c) Device operation: the electron occupation of a dynamic quantum dot is measured by observing the current flowing through the detector constriction.

current can be used to monitor the occupation of the dynamic quantum dots in the top channel.

Note that the current through a SAW channel is determined by the potential gradient at the channel entrance;[19] current conservation requires that beyond this point, small changes to the potential landscape will not affect the SAW channel current. In our device the SAW channel entrance is adjacent to gate G_{Inj}, around $8\,\mu$m from the detector constriction; too far for the detector constriction to affect the SAW channel current.

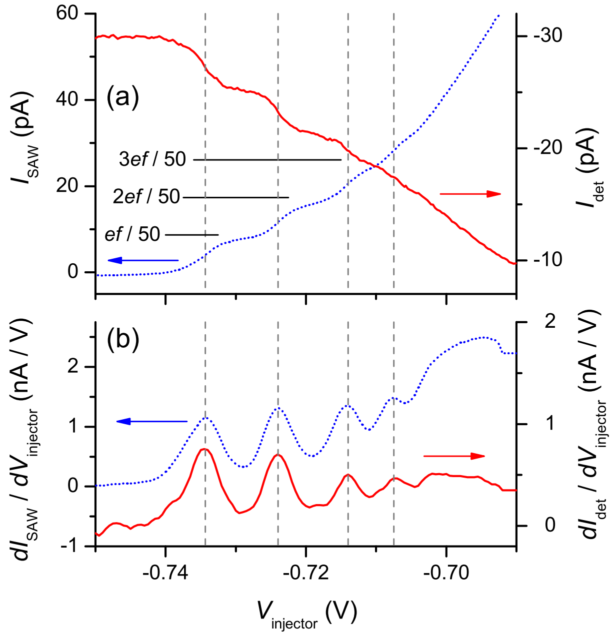

FIG. 2: (colour online). a) Current produced in the SAW channel (dotted line) and detector constriction (solid line) as a function of the injector gate voltage. b) Differential of the SAW channel (dotted line) and detector constriction (solid line) currents.

Whereas, the channel entrance of the detector constriction is immediately adjacent to the SAW channel, and so this is highly sensitive to charge in the dynamic quantum dots.

Figure 2 shows the effect of sweeping the injector gate. The SAW channel current (solid line) shows plateaux at multiples of 8.7 pA, which is $I_{SAW} = nef$ reduced by the $1 : 50$ pulse ratio;[20] the locations of plateaux are also shown by the minima in the differential of the SAW current. I_{det}, the crosstalk-induced current in detector channel (see below), can be seen to clearly follow the features in I_{SAW}, despite the fact that the gate being swept is $\sim 8\,\mu$m away from the detector circuit and would therefore be expected to have a negligible direct coupling to the detector current. However, I_{det} is sensitive to changes in the local potential landscape. The electrons which make up the acousto-electric current are carried through the channel in dynamic quantum dots, and so they are out of equilibrium with the reservoir 2DEGs. This means that the additional charge contained in the dynamic quantum dots increases the local electric potential, and so as the current carried in the dynamic quantum dots past the detector constriction is increased the constriction is closed, and the magnitude of the detector current decreases.

Note that the current through the detector circuit is negative. This is because the channel is sufficiently open for the current to be dominated by crosstalk (current generated by the interaction between the free-space electro-

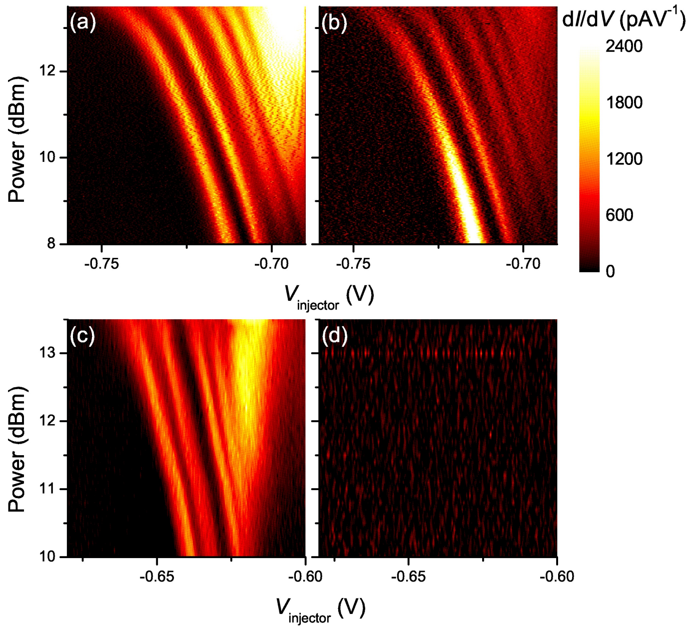

FIG. 3: (colour online). The differentials of the currents in the SAW and detector channels with respect to the injector gate voltage: (a) SAW channel and (b) detector constriction, where the SAW current is transported through the SAW channel in dynamic quantum dots; (c) SAW channel, and (d) detector constriction, where the SAW channel gate voltages have been backed off to allow an open one-dimensional channel of electrons to form in the SAW channel.

magnetic wave and the SAW)[21] rather than being a true acoustoelectrically-pumped current—it is experimentally known that crosstalk current can be positive or negative depending on various conditions (frequency, SAW amplitude, gate geometry)[20,22] for reasons that are not fully understood. The crosstalk current is more sensitive to changes in the local potential landscape than an acoustoelectric charge-pump current, and also has the advantage that it is approximately linear over tens of picoamp variation and so gives a uniform sensitivity, whereas if a charge-pump current was used in the detector circuit then the current plateau would lead to a non-linear sensitivity.

Figure 3(a) shows the differential of the top channel current as a function of the injector gate voltage and the power applied to the transducer. Acoustoelectric current plateaux are clearly visible as the dark bands in the plot. Figure 3(b) shows the equivalent data for the detector channel - the features in the top channel current are reproduced in the detector constriction current (the voltage applied to the detector gate (G_{D1}) is adjusted to reset the detector constriction current to -10 pA at the start of each sweep, because the detector channel current is strongly sensitive to the transducer power).

To demonstrate that it is the confined non-equilibrium charge in the dynamic quantum dots rather than the mere presence of electric current that controls the detector channel current, the voltages applied to the SAW channel gates G_{C2}-G_{C6} were backed off so that the channel was populated by an electron Fermi sea in the region defined by G_{C2}-G_{C6}. In this regime the electrons are pumped over the constriction at the injector gate and the current flows through the open 1D channel, but the SAW will be screened by the free electrons in the channel and so electrons are not confined to dynamic quantum dots as they pass the detector and there is no net increase in the charge close to the detector constriction. The differentials of the SAW channel and detector constriction are shown in Figs. 3(c) and (d).

The SAW channel behaves in a similar way to that as in Figs. 3(a) and (b), but the detector current does not record any features, as there is no non-equilibrium charge confined in dynamic quantum dots to change the channel current. This demonstrates that it is the non-equilibrium charge confined to dynamic quantum dots which creates an effect in the detector current, and not merely the fact that a current is flowing through the SAW channel.

In conclusion, we have demonstrated that a detector circuit may be used to observe the occupation of a SAW-defined dynamic quantum dot. The measurement is carried out non-invasively by using the effect of the change in the local electric potential caused by the non-equilibrium charge contained in the dynamic quantum dot. This technique is expected to be widely used as increasingly complex SAW devices are developed,[23,24] as non-invasive charge detection will be necessary both to test each component of a multiple-stage SAW circuit and to probe fundamental quantum effects in SAW devices (for example, as a “which path” detector[25] in a SAW quantum interferometer[5]).

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