Single photo-electron trapping, storage, and detection in a one-electron quantum dot

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There has been considerable progress in electro-statically emptying, and re-filling, quantum dots with individual electrons. Typically the quantum dot is defined by electrostatic gates on a GaAs/Al$_x$Ga$_{1-x}$As modulation doped heterostructure. We report the filling of such a quantum dot by a single photo-electron, originating from an individual photon. The electrostatic dot can be emptied and reset in a controlled fashion before the arrival of each photon. The trapped photo-electron is detected by a point contact transistor integrated adjacent to the electrostatic potential trap. Each stored photo-electron causes a persistent negative step in the transistor channel current. Such a controllable, benign, single photo-electron detector could allow for information transfer between flying photon qubits and stored electron qubits.

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The detection of a single photo-electron generally requires some type of gain mechanism. A new mechanism has emerged recently, photoconductive gain [1], for providing the sensitivity needed for single charge detection [2, 3, 4]. Indeed, the detection of a photo-hole is easier and more common than the detection of a photo-electron. The positive charge of a trapped photo-hole attracts electrons and leads to conventional positive photo-conductivity. Recently, single photon detection has been demonstrated by photo-hole trapping in defects [5] and self-assembled quantum dots [6] within semiconductors. The trapping of a photo-electron on the otherhand repels electrons and leads to conventional positive photo-conductivity. Photo-electron trapping has thus far been demonstrated in the microwave regime by photon-assisted tunnelling between Landau levels [7] and in an electrostatic quantum dot [8] with limited or no control over systematic emptying and injecting a single photo-electron. In this paper we report the trapping and detection of a single, inter-band photo-electron in a controllable electrostatic quantum dot.

The benefit of safely and gently trapping a photo-electron is that its spin information may be preserved. Favorable selection rules for information transfer between quantum states of photons and spin states of electrons in semiconductors have been identified [9]. It may become possible to transfer quantum information over long distances by exchanging information between flying qubits and stationary qubits [10].

It is essential that any new opto-spintronic device designed to achieve the above objectives accomplishes the following tasks: (i) trap a photo-excited electron in an artificially engineered trap; (ii) detect the stored electron by means of a benign gain mechanism; and most importantly (iii) ensure that the trap holds none but the single photo-excited electron. We experimentally demonstrate the injection and detection of a single, inter-band photo-excited electron, into an empty quantum dot defined electrostatically by metallic gates on a GaAs/AlGaAs heterostructure, with an integrated charge read-out transistor.

The signature of photo-electron trapping is negative photo-conductivity - a drop in the current through the detection circuit upon illumination [11]. Negative photo conductivity is commonly not observed in GaAs/AlGaAs heterostructures, though a persistent photo-induced increase in conductivity has been well known for some time now [12]. Positive photo-conductivity is a result of the
trapping of photo-excited holes and a subsequent increase in the 2D electron gas (2DEG) density. We have earlier reported the detection of such individual photo-hole trapping events with a simple split-gate geometry. Photo-holes are trapped predominantly by negatively charged defects at low temperatures known as DX centers. Persistent negative photo-conductivity at low temperatures has been reported only after the saturation of hole trapping centers, most likely ionized donors, and only at short wavelengths causing photo-excitation in the doped AlGaAs barrier layer.

On the other hand, photo-excitation in GaAs has always shown a positive increase in conductivity. Now, by creating an artificial electron trap defined by electrostatic metal gate electrodes, we have been able to detect the addition of a single photo-excited electron into the electron trap. We suppressed the usually dominant positive photo-conductivity by a shadow mask, that permitted the light to fall only in the immediate vicinity of the electrostatic quantum dot. A point contact field-effect transistor integrated adjacent to the dot serves to detect the injected photo-electron in a non-intrusive way. We believe that sensing a current directly through the quantum dot would be too invasive.

Our device is fabricated on a modulation doped GaAs/Al0.3Ga0.7As heterostructure grown by molecular beam epitaxy on a semi-insulating GaAs substrate. A scanning electron micrograph of the gate geometry of the device used in our measurements is shown in Fig.1. The gates are fabricated by electron beam lithography and electron-gun evaporation of Ti/Pt/Au. G1 and G2 define a quantum point contact (QPC) between the left source and drain Ohmic contacts, S_0 and D_0, respectively, shown in Fig.1a). Adjacent to this point contact, an electrostatic circular quantum dot with a lithographic radius of 200nm is defined by gates G3, G4 and G5. The electrostatic dot is defined by squeezing the 2DEG by the surface metallic gates. A variety of experiments have studied the properties of such GaAs/AlGaAs quantum dots in great detail, and a vast knowledge base has been developed.

Negative voltages on the five surface gates isolate a puddle of electrons in the 2DEG adjacent to the point contact transistor. Gates G3 and G5 together with G2 control the tunnel coupling of the electrons in the dot to the external 2DEG reservoirs, while gate G4 is used as a plunger to push electrons out of the dot one at a time down to the last electron. This creates an empty dot just before exposure to light. Photo-events over the bulk of the device are suppressed by a 150nm thick Aluminium layer deposited as a mask over the entire area of the device, except for a pin-hole aperture directly above the quantum dot as shown in the SEM of Fig.1b. An insulating SiO_2 layer and a thin adhesion layer of Titanium separate the metal gate electrodes from the Aluminium mask layer. Fig.1c shows the cross section view of the device layers.

We first present the electrical characterization of the electrostatic dot in Fig.2 and Fig.3. The device is cooled gradually to 0.43K in a 3He cryostat and negative voltages are applied to the five metallic surface gates defining the dot and the QPC. Fig.2 plots the current through the point contact transistor versus the plunger gate voltage, V_{G4}. The plunger is swept at a rate of 4mV/sec to repel electrons one at a time, into the surrounding 2DEG. It is important to detect the single electron tunnelling events and the trapped electric charge by means of an adjacent transistor, rather than by invasively passing current through the dot storing the electron. As an electron escapes the electrostatic quantum dot, the diminished electrostatic repulsion causes a jump in the QPC transistor current.

The quantum dot state at the start of the scan in Fig.2 is the same as at time t_0, (or equivalently t_0) in Fig.3. Upon formation, a few excess electrons remain trapped in the dot in a long lived meta-stable state, prior to being forced out by the plunger gate. The point contact current varies in a saw-tooth fashion with a small discrete positive step for each electron ejected as seen in Fig.2. The last electron emission event occurs on curve (c) at a voltage of about G4=-2.75V on the plunger gate. In order to ensure that the absence of further steps is not due to very slow tunnelling times, the barrier gate voltage G3 was raised just after the last detected step to allow any remaining electrons to escape. Only a smooth increase in the QPC current could be observed due to the
The transistor, associated with the transition of the dot from the meta-stable filled state to the equilibrium empty state. The current switches from \( I_1 \) to \( I_2 \) as the G4 plunger gate ejects stored electrons in the cycle from \( t_0 \) to \( t_2 \). When the barriers are re-opened and closed in the cycle from \( t_3 \) to \( t_6 \), electrons remain trapped in the dot restoring the current to \( I_1 \). The color of the vertical transitions is coded to the color of the corresponding gate switch for that transition. Level \( I_2 \) represents the desired empty state of the dot, at which it is ready to accept and trap photo-injected electrons.

Capacitive coupling between the point contact and the tunnel barrier gate with no evidence for any remaining electrons. Electron tunnelling from the dot in this regime is essentially a statistical process, but it is sped up according to the G3, G4, G5 gate voltage settings. The lower inset to Fig.2 shows the steps corresponding to the last electron step is 0.5nA providing an excellent signal to noise ratio.

Upon sweeping the plunger gate G4 back up to -1.5V from -4V at the same scan rate as in the forward direction, no electrons were observed to re-enter the dot. The equilibrium state of the dot at \( V_{G4} = -1.5V \) is the “empty dot” state, since by that point, the dot energy levels have been raised well above the external Fermi level. Fig.3 illustrates the hysteretic behavior of the QPC transistor source/drain current associated with the emission of electrons from the dot. Immediately following time \( t_0 \), and equivalently time \( t_6 \), the dot exists in the meta-stable state with excess trapped electrons. The thick tunnel barriers formed in our geometry when G3 and G5 are at -0.9V prevent fast tunnelling. No electrons were observed to escape in the interval between time \( t_0 \) and \( t_1 \), while at \( t_1 \) they are forced out. The electron emission associated with the slow 5 minutes ramp in Fig.4 occurs within the plunger rise-time at \( t_1 \) in Fig.4. The gate voltage changes at \( t_1, t_2, t_3, t_4, t_5 \) all lead to an equilibrium electron density.

The QPC current level \( I_1 \) represents the filled meta-stable dot state and level \( I_2 \) the empty state, at which the dot is ready to accept and hold only the photo-injected electron with a storage time longer than 5 minutes.

Highly attenuated light pulses at a vacuum wavelength \( \lambda=760nm \), which photo-excite inter-band electrons in the GaAs layer, were created by a Pockels cell modulator at the output of a cw laser. The pulses were focused onto a spot size of about 100μm diameter on the sample. The opaque Aluminium mask blocks almost all of the incident photon flux except directly above the electrostatic dot where there was a 200nm radius pin-hole aperture. Assuming a Gaussian profile for the incident spot over the illumination area of radius 50μm, and given the 200nm radius of the electrostatic dot, the photon flux into the dot is reduced by a factor of \( 10^{-5} \) compared to the total incident flux.

Fig.4 which plots the QPC transistor current versus time, presents a typical experimental result of exposure to a series of consecutive pulses after emptying the dot, prior to the first pulse. In this figure, the incident photon flux was maintained at 0.1 photons/pulse within the dot area. Time \( t=0 \) marks the time at which the Pockels cell was opened, for a pulse duration of 150μsec. When a photon is absorbed within the active area, and the photo-electron gets trapped in the dot, a sharp drop in transistor current is seen for pulse 21 in the series. The current step size is consistent with the expected single electron steps determined from the electrical characterization in Fig.2. After emptying the dot by the plunger gate G4, if even any one of the gates G3,G4 or G5 is grounded, the quantum dot is open and negative photo-conductucity steps were not observed. We thus rule out the possibility of negative photo-conductucity steps due photo-electron
trapping in donors, DX-centers and traps in the SiO₂ layer. The fall time associated with the single electron signal is 20μsec, from Fig. 4(b), consistent with the speed of the pre-amp that was used. Given the signal-to-noise ratio in Fig. 4(b), this leads to a single photo-electron signal to noise ratio of about 10⁻³ electrons/√Hz.

Increasing the photon flux over the dot increases the frequency of occurrence of negative photo-conductivity steps. Fig. 5 shows a series of traces for a photon flux of 1.2 photons/pulse into the dot with no reset to empty the dot between pulses. Based on the frequency of occurrence of photo-detection events, we estimate the photo-electron trapping quantum efficiency to be about 10%. This is consistent with the penetration depth of λ=760nm light, and the size of the electrostatic potential dot. Inter-spersed among the negative steps, some positive steps were occasionally seen, as in the 34th pulse in Fig. 5. Such positive signals were seen with a 1% occurrence rate and can be attributed to the photo-ionization of residual neutral donors close to the quantum dot. The occasional positive steps were more noticeable when the dot held several photo-electrons, possibly due to the additional mechanism of photo-electron ionization or photo-hole annihilation within the dot. The positive steps are rare since almost all the photo-holes are swept away by the surrounding negatively biased gate electrodes.

In conclusion, we have demonstrated single photo-electron trapping and storage in an empty electrostatic quantum dot that can be controllably created prior to photo-excitation of inter-band electrons. Recently, experiments demonstrating the electrical measurement of a single electron spin inserted in a similar electrostatic dot or in a commercial Si field-effect transistor have been reported. The successful trapping and detection of photo-electrons reported here, in spite of the usually dominant positive photo-conductivity, would enable the implementation of a detector for an optically injected spin. By combining the single photo-electron trapping result reported in this paper, with the single spin measurement reported in [13], it would be possible to convert a flying qubit (photon) into a stationary qubit (trapped electron) and to measure the spin state.

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