HEMT Amplified SET Measurements of Individual InGaAs Quantum Dots

K. D. Osborn, Mark W. Keller, R. P. Mirin

National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305

Abstract. A high electron mobility transistor (HEMT) is used with a single-electron transistor (SET) to measure single electrons tunnelling into individual InGaAs quantum dots. The SET detects a change in location of an electron once it tunnels from an underlying n-doped layer into a quantum dot lying in an intermediate layer. A HEMT on the He\textsuperscript{3} stage with the SET is used to extend the measurement bandwidth to 400 kHz. We demonstrate this technique with a measurement of the Stark shift in the first electron state of the quantum dot as a function of lateral electric field.

The electron states of individual self-assembled quantum dots must be controllably occupied in order to develop a quantum dot-based electrically-triggered single-photon source. Here and in previous work [1], we measure individual electrons tunnelling into quantum dots with a single-electron transistor (SET). However, in this work we have increased the bandwidth of the measurement, which allows us to quickly obtain the energies of electron states as a function of applied fields. We demonstrate our improved technique by measuring the Stark effect in the ground state of a quantum dot as a function of the applied lateral electric field.

By themselves SETs typically have a low bandwidth since the high resistance across the SET electrodes is coupled to wiring that capacitively filters frequencies greater than approximately 1 kHz. In order to improve the bandwidth of SET measurements, high electron mobility transistor (HEMT) amplifiers [2] and RF amplifiers [3] have been used. We have selected a commercially available GaAs HEMT chip in our application. The HEMT has the advantage of being small and inexpensive compared to a RF amplifier, and therefore several SETs can be amplified with HEMTs in a single cooldown of the dewar.

A schematic of the SET and HEMT, including the capacitively coupled quantum dot and gates, is shown in Fig. 1. The SET is current-biased with a 15 M\ohm chip resistor, and the SET voltage \( V_{SET} \) is sent to the gate of the HEMT chip. Along with the SET, the resistor and HEMT are on the sample stage of a He\textsuperscript{3} dewar, which allows for a small stray capacitance to ground. Since \( V_{SET} \) is small, the source-gate bias is controlled by a voltage \( V_{SO} \) applied to the source. The HEMT is biased with a large resistor on the drain lead to keep the power dissipated by the HEMT at about 1 \( \mu \)W. The bandwidth in this configuration is 400 kHz, which allows us to take data significantly faster than for our previous measurements on quantum dots.

The Stark effect has been observed in excitons from InGaAs quantum dots by applying a vertical electric field to the quantum dot layer embedded within a p-n diode [4]. In addition, the vertical and lateral Stark shift have been theoretically studied in an InAs/GaAs quantum dot [5]. Here we study the lateral Stark shift in the first electron state of a quantum dot. Since the vertical Stark shift is small compared to the lateral shift in our measurement, we will avoid discussing the vertical shift below.

Measurements are taken on a heterostructure containing, from bottom to top, an n-doped layer of GaAs, a GaAs tunnelling barrier, a layer of InGaAs quantum dots,
and finally GaAs and AlGaAs capping and blocking layers, where the thicknesses are given in ref. [1]. The nominal quantum dot density is $2 \times 10^{10} \text{cm}^{-2}$, as measured from an atomic force microscope image of a wafer of uncapped dots grown immediately before the wafer with the completed structure. Room-temperature photoluminescence revealed a ground-state exciton peak at 1160 nm. In this work we have fabricated an SET using e-beam lithography and Al evaporations at three angles to produce a 80 nm $\times$ 120 nm island connected to two overlapping electrodes by tunnel barriers and capacitively coupled to two neighboring gates, as shown in the inset to Fig. 2.

In the device, electrons with electrochemical potential $-eV_n$ are tunnelled from the n-doped layer into the quantum dots, near an overlying SET. The SET is amplified with the HEMT circuit described above. The voltages applied to gate 1 and 2 are respectively $V_{G1} = V_S + V_{FB}$ and $V_{G2} = -V_S + V_{FB}$, where $V_{FB}$ is the SET feedback voltage and $V_S$ is proportional to a lateral electric field. The chemical potential for electron N in the quantum dot is

$$\mu(N,V_S)/e = (\eta_n - 1)V_n + (\eta_{G1} - \eta_{G2})V_S + (\eta_{G1} + \eta_{G2})V_{FB}$$

(1)

for a lateral electric field set by $V_S$. For our data, $\mu(N,V_S)$ can be expressed as $\mu_0(N) - \alpha(V_S/d)^2$, where $d$ is an effective length that creates the absolute value of the lateral field at the quantum dot $|V_S/d|$, and $\alpha$ describes the strength of the Stark shift. The electrochemical potential of the quantum dot is shifted by voltages applied to the n-doped layer, gate 1, and gate 2 through the dimensionless coupling coefficients, $\eta_n$, $\eta_{G1}$, and $\eta_{G2}$, respectively.

In Fig. 2, a plot of $dV_{FB}/dV_S$ is shown as a function of $V_n$ and $V_S$. The dark points fall along curves that indicate that an electron has tunnelled into a quantum dot. Approximately parallel curves correspond to electrons with a different N tunnelling into the same quantum dot. Three curves marked with pairs of solid arrows show the first 3 electrons tunnelling into a quantum dot under the body of the SET, which we analyze below. For the addition of a particular electron number, the points in $V_n$ and $V_{FB}$ are fit to second order polynomials in $V_n$. The quadratic dependence as a function of $V_S$ in the lowest curve marked by solid arrows reflects a Stark shift in the chemical potential $\mu(1,V_S)$. To solve equation (1), we use the value $\eta_n = 1/3$, obtained in ref [2], and $(\eta_{G1} + \eta_{G2}) << 1$. This yields the chemical potential of the first electron level, $\mu_0(1) = 291$ meV, and the first two addition energies, $\mu_0(2) - \mu_0(1) = 23$ meV and $\mu_0(3) - \mu_0(2) = 38$ meV. The curvature in the N= 1 data yields $\alpha/d^2 = (1.8 \pm 0.3) \times 10^{-3}$ eV/N, where the uncertainty in $\alpha/d^2$ is determined from the uncertainty in $(\eta_{G1} + \eta_{G2})$. If we estimate the effective distance as $d=100$ nm, we obtain $\alpha \approx 1.8 \times 10^{-17}$ em$^2$/N, which is approximately 2.5 times smaller than a value obtained from a calculation of

![FIGURE 2. $dV_{FB}/dV_S$ as a function of $V_n$ and $V_S$. The inset shows the SET structure made with three sequential depositions at angles $\phi_1$, $\phi_2$, and $\phi_3$.](image)

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