



CONDUCTION OF ELECTRONS IN GATE-DEFINED QUANTUM DOTS

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Introduction

In this chapter we explore transport properties of lateral, gate defined quantum dots in GaAs/Al, Ga, As heterostructures. The term "quantum dot" as defined here refers to small regions of charge carriers within a 2-dimensional electron gas (2DEG), established via electrically biased surface gates used to isolate the charge carriers from the rest of the 2DEG, which are confined to length scales on the order of nanometres. While there are several other forms of quantum dots, including colloidal and self-assembled dots, in this chapter, however, we consider only gate defined quantum dots.

Recent advancements in the research areas of quantum dot (QD) and single electron transistors (SET) have opened up an exciting opportunity for the development of nanostructure devices. Of the various devices, our attention is drawn in particular to detectors, which can respond to a single photon over a broad frequency spectrum, namely, to infrared (IR) frequencies, we report transport measurements of weakly coupled double quantum dots, fabricated on a GaAs/AlGaAs 2 dimensional electron gas material, under the influence of external fields at 110GHz. In this experiment, transport measurements are carried out for coupled quantum dots in the strong-tunneling Coulomb blockade (CB) regime. We present experimental results and discuss the dependence on quantum dot size, 2DEG depth, fabrication techniques, as well as the limitations in developing a QD photon detector for microwave and IR frequencies, whose noise equivalent power (NEP) can be as sensitive as 10 w/Hz.

The charging energy E_c of a quantum dot is the dominant term in the Hamiltonian and is inversely related to the self capacitance of the dot C_{ot} according to $E_c = e^2/C_{ot}$. The temperature of the charge carriers within the 2DEG must be kept below a certain value, namely KT , so that the thermal energy of the electrons does not exceed the charging energy E_c of the dot. Keeping the temperature below the KT limit prevents electrons from entering

or leaving the dot at random, thereby allowing one to control the number of electrons in the dot. In order to raise the operating temperature T of the raise the charging energy E_c , which is single photon detector we must also accomplished by decreasing C_{ot} Since C_{ot} is directly related to the dimensions of the quantum dot our focus was directed at decreasing the overall size of the quantum dots. For smaller gate-defined quantum-dots the inclusion of shallower 2DEG is necessary.

However the experiments that we carried out to determine the effect of 20EG depth on lateral gate indicated that leakage currents within a GaAs/AlGaAs heterostructure increased dramatically as the 2DEG depth became shallower AT this moment the leakage current in shallower 2DEG materials is one of the most significant technical challenges in achieving higher operating temperature of the single photon detector.

Gate-defined quantum-dots

2-dimensional electron gas (2DEG)

In contrast to colloidal and self-assembled quantum dots, which are physically well defined small dots separated from other media, the gate-defined quantum dot means charge carriers (either electrons or holes) confined in a small region, which is formed by electrically biased gates surrounding the region. First the charge carriers are confined within the so-called 2-dimensional electron gas (2DEG) material, which is typically made of GaAs/AlGaAs heterostructure. Figure 6.1 shows an example of the vertical profile of 2DEG heterostructure and the corresponding energy band diagram.

At low temperature each Si atom produces a free electron as the electrons become thermally ionized [2, 3]. The offset in the conduction bands between GaAs and AlGaAs results in each free electron migrating toward the energetically favorable GaAs substrate layer. The charge carriers still feel the electrostatic attractive forces from the ionized donor atoms, however, and ultimately become trapped at the interface between the GaAs layer and an undoped AlGaAs layer. These trapped electrons are called 2-dimensional electron gas (2DEG). As the temperature decreases to very cold temperatures (< 1 K) the thermal smearing of the vertical "z" profile of the 2DEG becomes less pronounced as the electrons occupy only the lowest energy levels up to the Fermi Energy, resulting in a very clean glass of electrons confined within a 2-dimensional plane.

Because the lattice constants of GaAs and AlGaAs are only slightly different (~7% mismatch) the interface is essentially defect free. Because of this defect free interface and the separation of the 2DEG from the Si dopants 2DEG can have high electron mobility, $H. 10^{-}$

10⁷ cm²/v/s, and long mean free paths, 100-1000 nm. These properties are often exploited for quantum dot devices which require coherent and ballistic electron transport behavior.

Gate-defined quantum-dot

The local electron density within the 2DEG can be manipulated by placing electrodes on GaAs cap surface, as shown in Figure 6.1, When a negative bias voltage is applied to the electrodes the negatively charged gates repel electrons in the 2DEG. If the negative field strength is strong enough all electrons beneath the electrodes will be fully depleted. The electrodes can be lithographically arranged over an area with a certain geometric shape, such as a circular disk. An example is shown in Figure 6.2.

With strong enough negative bias voltages applied to the electrodes, electrons confined inside the area (e.g. circular disk) will be isolated from the rest of the electrons in the 2DEG. These isolated electrons in the area (e.g. disk) are called the gate defined quantum-dot and the rest of the electrons in the 2DEG are called the reservoir. While the configuration of the gates influence the overall shape and determine the maximum size of quantum dot, actual shape and size of the isolated electron puddle (e. quantum dot) are dependent upon the strength of the negative bias voltage applied to each gate. The gap between gates is often called the quantum point contact (QPC) and is typically a few tens of nm. It pinches off electrons when the negative bias voltage is applied to the gates. The QPCS can individually tune the potential barriers between the dot and the reservoirs, and hence control the tunneling rate from the leads and the dot. The transport through a quantum dot can be divided into two categories, "open" and "closed," depending upon the conductance of the QPCS. For strong coupling, the conductance $G > e^2/h$, where each QPC passes one or more modes, the dot is considered "open." In an "open" dot electrons are classically allowed to travel through the dot from one reservoir to the other. For weak coupling, $G < e^2/h$, where each QPC is set to pass less than one fully transmitting mode, the dot is considered "closed." If the bias voltage is large enough the electrons near the quantum point contacts are completely pinched off, making the quantum dot to be "closed" or isolated from the reservoir, However electrons can tunnel through the "closed" quantum dot, allowing very small currents. Therefore the conductance is orders of magnitude lower than that of 2DEG.

The Coulomb blockade occurs due to the fact that conduction through the dot is prevented for most settings of the electrostatic gates simply because the available energy levels within the dot are not in alignment with the Fermi levels in the source and drain (i.e. reservoir). An electron is unable to tunnel into the dot if the energy needed to add an additional electron (from N to N + 1 electrons) is above the Fermi Energy in the source.

Similarly an electron is unable to tunnel out of the dot if the energy carried by that electron is less than the Fermi Energy in the drain. If electrons have enough energy to tunnel into the dot and then tunnel out of the dot, the measured conductance displays a large conductance spike, which indicates tunneling currents. This is known as a Coulomb blockade peak.

For the tunneling currents and the Coulomb blockade five separate energy parameters need to be considered, including the source-drain voltage V_{sd} , the chemical potentials of source μ_s and drain μ_d , the charging energy E_c and the thermal energy of charge carriers kT . For the conductance measurement a small source-drain voltage V_{sd} which is typically limited to be less than a few μV so as not to impart energy to the electrons greater than the thermal energy, is held across the dot. The source-drain voltage results in the chemical potential difference between the chemical potentials of source and drain $\mu_s - \mu_d = eV_{sd}$. The charging energy E_c is an additional Coulomb energy that is needed to add an additional electron to the quantum dot, and can be expressed as

Here C_{dot} is the self-capacitance of the quantum dot. At temperature T an electron has the thermal energy kT . If the thermal energy becomes comparable or larger than the charging energy it causes the electron randomly to tunnel through the quantum dot, and also results in a thermal broadening larger than the energy level spacing. Then the quantum dot will not be functional, as the electron is no longer controllable by the gate bias voltage. Hence it is very important to keep the quantum dot at very low temperatures so that its thermal energy is well below the charging energy (i.e. $E_c > kT$),

A single photon detector based on coupled double quantum dots

The quantum energy levels as well as the level spacing A can be adjusted by controlling the physical parameters of the quantum dot. A photon can change the energy level of a quantum dot, which leads to electron tunneling through the quantum dot. This is known as photon assisted tunneling in a quantum dot. In 2000 Komiyama and his coworkers exploited this property and developed a detector, which can detect a single photon at far-infrared frequencies. The quantum dot size that they used in the experiments was about 500 nm in diameter fabricated on a 100 nm thick 2DEG substrate. Their large quantum dots resulted in a large self capacitance C and a small charging energy $E_c = e^2/2C$. Hence their detectors had to be operated at 100 mK or below, which made the detector less practical. We attempted to adopt their quantum dot detector technology and raise the charging energy and the operating temperature by reducing the quantum dot size.

A shallow 2-dimensional electron gas for quantum dot single photon detector

For the design of our quantum dot detector we have performed numerical calculations. The calculations indicate that our detector should be fabricated on a shallow 2 dimensional electron gas (2DEG) substrate in order to achieve an operating temperature.

The high-mobility GaAs/Al_{0.2}Ga_{0.8}As heterostructure crystal was grown by molecular beam epitaxy in the 1001 direction. The heterostructure layers were deposited on an n-type GaAs substrate, carried a 5000 Å thick GaAs buffer layer, a non-inverted heterostructure (500 Å thick GaAs/ 140 Å thick Al_{0.24}Ga_{0.76}As), a p-doped barrier layer (250 Å thick Al_{0.24}Ga_{0.76}As), and a δ-doped GaAs cap layer (10 Å thick). The silicon n-type dopants (level 6x10¹⁸/cm³) provide the excess charge carriers (target value was 6x10¹⁸/cm³ at room temperature), which constitute a 2 dimensional electron gas (2DEG) at the hetero-interface 400 Å below the wafer surface and 140 Å from the dopant atoms.

For the characterization of 2DEG as well as for the quantum dot device good ohmic contacts should be made on the GaAs cap layer, as illustrated in Figure 6.1. A good ohmic contact has energy a non-zero internal resistance R_c that obeys Ohm's law for all current densities of interest. The contact should work at the lowest temperatures reached in quantum dot experiments where thermionic currents are negligible, but tunnel currents are allowed [5-7], Fabrication of good ohmic contacts is not always trivial. The standard process includes depositing metals onto the surface and then annealing them into the wafer in order to make electrical contact to the 2DEG.

The first Ni layer acts as a wetting layer and enhances the uniformity of the contacts, 5 nm is enough as this layer should not be thick. Otherwise it may prevent the other elements from penetrating into the wafer. The 2:1 ratio of Au:Ge forms a eutectic mixture, which is the ratio of two substances with the lowest melting point (a 2:1 ratio is essentially 88% Au and 12% Ge by weight with the melting point of this eutectic at 380°C), Each metal was evaporated one at a time. The second Ni layer acts as a barrier for the top layers of metals. The metalized 2DEG substrate is then submersed in Acetone for liftoff, and then rinsed with IPA and DI-H₂O. Finally it was dried by blowing dry N₂ gas.

In order to make electrical contact to the 2DEG the metals must be annealed into the substrate after the liftoff process.

The resulting R_c resistances for each contact are on the order of tens of k Ω at room temperature and decrease to a value on the order of k Ω at 4.2 K for the 160 nm deep 2DEG.

For the shallower 2DEGS the contact resistances are even lower; they are on the order of $k\Omega$ at room temperature.

After the success in Ohmic contact fabrication the 2DEG was characterized by measuring the Hall properties of micron size Hall bars, which were fabricated on the 2DEG material. A standard Hall bar geometry, which is shown in Figure 6.8, is defined by wet etching and the metallic electrodes and ohmic contacts are patterned via optical lithography. Hall measurements reported in this chapter were taken on a 50 μm wide Hall bar with a 700 μm distance between longitudinal taps. Electrical contact is made with the 2DEG by lithographically patterned Ni-Au-Ge Ohmic contacts, which when annealed at temperatures above 400 degrees Celsius provide for low resistive transport into and out of the 2DEG at cryogenic temperatures.

Two different Hall bars were fabricated, with and without an overlaying Si_3N_4 (silicon nitride) dielectric layer, which was tested to shield the 2DEG along the mesa. For the edge from unwanted field effects caused by voltage biased leads, characterization of ohmic contacts we used a standard Van der Pauw experimental configuration. As shown in Figure 6.6, the resistivity decreased with temperature monotonically indicating the correct Ohmic contact behavior.

When a magnetic field is applied to 2DEG, electrons moving within the 2-dimensional system experience a Lorentz force that pushes them into circular orbits. Since in the 2 dimensional system only certain orbits (or energy states) are quantum mechanically allowed, the energy levels of the circular orbits are quantized, just as in the discrete set of allowed energy levels in an atom. These quantized energy states, or Landau levels, can be expressed as

where N is the number of orbits that can be packed per Landau level into each cm^2 of the system. At various points along the magnetic field all electrons fill up an exact number of Landau levels with all higher energy states remain empty. When this occurs the B-field is quantized and can be expressed as

where n is the electron density for a given state. Then the magneto resistance resistance measured along the initially supplied current path (longitudinal resistance R_{xx}) becomes quantized as

The first expression is just the classical Hall resistance while the second expression comes from substituting the values for B into the first expression. From this equation it is

possible to extract the charge carrier density of the material by examining the periodicity of the plateaus in the quantum Hall effect measurement.

Our Hall resistance measurements were carried out on a patterned Hall bar shown in Figure 6.9. A drive current of 10 A, which was the minimum current setting available on our Physical Properties Measurement System at a frequency of 30 Hz was supplied across the length of the Hall-bar, and a magnetic field B was applied along the direction perpendicular to both the current path and the measured V . direction. A 9 Tesla superconducting magnet was used to generate the field, though for safety purposes the magnet was only ramped to 7 T in each direction. The measurements performed at 1.7 K

From the periodicity of the plateaus in Figure 6.10 (a) and (b), the 2DEG charge carrier density n was estimated to be about 5.0×10^{11} charges/cm² while the charge carrier mobility was estimated to be about 3.0×10^4 cm²/V.s. These two parameters were then used to obtain for example the Fermi Energy E , mean free path Fermi wavelength λ , and effective mass m . Table 6.2 lists the various properties that were calculated for one of our shallower (40 nm thick) 2DEGS.

Fabrication of gates on a shallow 2DEG and gate-defined double quantum dots

A Quantum Point Contact is defined as a short one dimensional channel Ohmi connected adiabatically to large source and drain reservoirs and that supports one more wave modes. Here QPCs were made by electron beam lithography where 10 small metallic electrodes are patterned to form a small gap between them (100 nm to 1 μ m in a typical QPC experiment). When the device is very cold and the negative bias voltage applied to it is strong enough to fully deplete electrons in the local 2DEG underneath, the electrons within the 2DEG are forced through a narrow constriction having now been permitted to move in only one direction. The width of the channel can be controlled by adjusting the gate voltages and can be made small enough to be comparable to the Fermi wavelength of the electrons (40 nm). When the wavelength of the electrons is on the order of or greater than the characteristic size of the system quantum effects become pronounced. Here, since the Fermi wavelength is comparable to the width of the QPC's narrow constriction quantum effects are observable. Figure 6.11 shows examples of QPC's while Figure 6.12 shows a quantized resistance obtained from a QPC shown in Figure 6.11 (a), which indicates the quantization of the conductance in the QPC.

Weakly coupled double quantum dot for a single photon detection application

For a small number of electrons in the quantum dot it is possible to calculate many electron wave-functions and energy states. The many-body spectrum at zero magnetic field is then governed by the quantum confinement energy E_c , and the charging energy.

If one uses the quantum dot as a photon detector, the characteristic frequency is related to the frequency of the photon absorbed by the quantum dot. This means that the photon frequency of the quantum dot detector can be tuned by adjusting the electrostatically defined quantum dot size. When a photon is absorbed by the dot its energy level is shifted resulting in a pair of excited electrons and holes. The excited charge can tunnel to the electron reservoir (i.e. outside of the quantum dots), resulting in the conductance-resonance peak shift. The variation of conductance can be detectable when the quantum dot absorbs even a single photon. As demonstrated by Komiyama and his coworkers [10, 11], such photon detection can be achieved using a single quantum dot or weakly-coupled double quantum-dots. Since the photon detection using double quantum-dots seemed to be more practical than that of a single quantum dot, which can be achieved by applying a considerable magnetic field (3.4 - 4.15 Tesla) to the quantum dot, we adopted the double quantum-dot technique.

Double quantum dot photon-detector

Our single photon detector consists of double quantum dots in a parallel geometry that is defined by metallic electrodes deposited on the 2DEG substrate surface. In this experiment we have used several different 2DEG substrates with the 2DEG depth ranging from 40 nm to 160 nm, and fabricated more than several hundred devices. Figure 6.14(a) shows the gate electrodes and the Ohmic contacts with the quantum dots located at the center of the white frame. Figure 6.14 (b) shows another SEM picture of the double quantum dots, which is a magnified view of the center part of Figure 6.14(a). The lower quantum dot (QD1) acts as a photon absorber and the upper quantum dot (QD2) functions as a single electron transistor.

The gate electrodes were defined via e-beam lithography after which we deposited a 50 Å thick Cr layer (acts as a wetting layer) on the surface of a GaAs/AlGaAs heterostructure and then a 150 Å thick Au layer on top of the Cr layer. The diameters of QD1 and QD2, as defined by the surrounding electrodes, are roughly 250 nm with the diameter of the SET dot (QD2) slightly smaller than that of the absorber dot (QD1). As mentioned earlier, the actual size of the quantum dot is dependent upon the strength of the negative bias voltage applied to the gates: the stronger the bias voltage the smaller the quantum dot. As the

capacitance and the electrochemical potential of the quantum dot are closely related to the number of isolated electrons, one can control the capacitance and the electrochemical potential by adjusting the gate voltage. The plunger gate G, shown in Figure 6.14 provides experimental control of the SET dot's self capacitance (C_s) and electrochemical potential (μ), and the pair of gates labeled G, control the absorber dot's self capacitance (C_a) and electrochemical potential (μ_a). The electrodes labeled G, control the potential barrier that couples the SET dot and the absorber dot. As the absorber (QD1) and the SET (QD2) are weakly coupled by the voltage on gates G, the excited energy level of the absorber alters the energy levels of the SET. If an energy level of the SET aligns within the energy levels of the source and the drain, electrons begin to flow through the SET. These excited energy levels of the absorber and the SET are in what are referred to as meta-stable states, which survive typically on the order of or less than a few milli-seconds. This short meta-stable state is due to the fact that a finite probability exists that an electron from one of the large 2DEG reservoirs "hops" onto the absorber dot. This results in a change in the energy of the absorber dot, which can affect the energy level matching between the SET dot and source and drain, since the two dots are electrostatically coupled.

The electrons ($\sim 10^{-10}$) flowing through the SET result in an electric current, which is on the order of a pico-Ampere (10^{-12} A) or less. [1, 3, 12-14] In order to measure this weak current one should carefully design the experimental set up. Since electrical noises can induce currents much larger than pico-Ampere, it is necessary to minimize ambient electrical noises, which usually can be achieved by carrying out the measurements within a shielded room, and also by employing a lock-in technique. [15-17] An example is shown in Figure 6.15. A measurement includes the application of a source-drain voltage (or current source) over the device, or part of the device, and measuring the resulting current or voltage signal as a function of various parameters, such as the negative voltages applied to the depletion gates, temperature, electromagnetic fields, etc.

Photon detection

A schematic diagram of our photon detection setup is shown in Figure 6.16 to modulate the signal we split the micro coaxial cable and made two sets of dipole antennae, which face each other across an optical beam chopper set to produce 1 2 1 modulation. However, at the low modulation frequency, the chopper's blade did not rotate smoothly resulting in irregular modulation so much that the modulation interval was highly irregular. Also, we note that the millimeter wave signal was highly attenuated through the micro-coaxial cables, as well as through the dipole-antenna to dipole antenna coupling. We estimate

the attenuation rate was much more than 5 dB per foot for the micro-coaxial cable and the coupling efficiency through the dipole-antenna coupling to be less than 10%. Since the initial mm wave input was approximately 50 W. and the transmission efficiency of the millimeter wave photon through the coaxial cable and the dipole-antenna coupling was extremely poor, we think that the millimeter wave signal radiated onto the double dot detector was sub-microwatts.

We measured the temperature dependent conductance as well as the bias voltage dependent conductance of our double dot device. The experiments indicate that although the millimeter-wave signal power was very weak our double dot device could detect the signal (Figure 6.17). However, the results may not indicate single photon detection. We think that our double dot detector could detect a few millimeter-wave photons at 100 mK.[18]

While experiments indicate that it was possible to detect some photons at 110 GHz with the double quantum-dot structure shown in Figure 6.14, the detection efficiency was very poor. We suspect that the inefficiency was largely due to the gate G2, which was supposed to function as an antenna. With its improper shape as an antenna, it did not efficiently pick up photons. Later we modified the double quantum dot detector, implementing bow-tie antenna geometry for the gate G2, as shown in Figure 6.18. Also we attempted to reduce the quantum dot size in order to detect photons at an elevated temperature. As discussed earlier, a quantum dot detector should be operated at a temperature T that has a thermal energy kT below the charging energy of the quantum dot. The charging energy E_c , is given as $E_c = e^2/C_{dot}$ Where C_{dot} is the self capacitance of

Leakage currents in GaAs/AlGaAs heterostructures

Our experiments revealed that the quantum dot detectors fabricated on a shallow 2DEG suffered from problems associated with overwhelming leakage currents. Within a GaAs/AlGaAs heterostructure the leakage currents increased dramatically as the 2DEG depth became shallower. Since the leakage currents dominate, it was not possible to obtain any discernible signal from the quantum dot detector. Also the leakage currents caused severe damage to the quantum dot gates, often resulting in a short circuit on the gates.

Measurements were performed to determine the currents that flow between the 2DEG and a laterally defined depletion gate on the wafer's surface. Current is measured as a function of the voltage applied to the gate when the gate is biased with respect to the 2DEG underneath. While we expect that the current should be zero ideally or much less than pico-Amperes, the actual leakage current measured is orders of magnitude larger than anticipated. Even our numerical calculation, which was performed along with our experimental efforts,

indicates that the leakage current is substantially larger than previously expected for shallow 2DEG wafers. Unless we find a way to prevent this large leakage it may lead to a limit for the maximum operating temperature obtainable for our quantum-dot photon detector.

The leakage currents increased 6 orders of magnitude when the 2DEG depth was varied from 160 nm to 40 nm. Some of the shallowest (40 nm) 2DEG substrates generated leakage currents as high as tens of micro-Amperes, while the leakage current from the thickest one was much smaller, less than a pico-Ampere. When leakage currents are as high as several micro-Amperes the electron flow in and around the quantum dots cannot be controlled, and it is impossible to obtain any meaningful signal from the quantum dot detector. Our experiments further revealed that the strength of leakage currents vary depending on the individual 2DEG substrate. In other words, when we measure the leakage currents from two different 40 nm thick 2DEG substrates, we obtain very inconsistent results. This suggests us that the leakage current problem may not be entirely due to the intrinsic property of a shallow 2DEG, rather it may suggest that the problem is related to the defects in the 2DEG substrate.

The simulations indicate that a shallower 2DEG leads to a larger leakage current, and the leakage current can exceed a thousand nano Amperes, These results are at least qualitatively consistent with our experimental results. A simulated result that shows the leakage current as a function of gate voltage is presented in Figure 6.21. Apparently the exponential relationship between the leakage current and the bias voltage is not consistent with our experiments. (See Figure 6.20) The discrepancy may be due to the fact that our model is too simple and does not reflect realistic conditions, for instance the scattering that the charge carriers experience, due to the Si dopants, as they pass from the lateral surface gates to the 2DEG, and the effect of lattice mismatching between GaAs and AlGaAs. In order to construct a device using quantum dots, one should minimize the leakage current since it not only prevents the proper control of the quantum dot but also sometimes leads to physical damage to the quantum dot. The gates surrounding the quantum dot are very small, typically less than 20 nm thick and a few tens of nm wide.

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