STUDY ON THE CONDUCTION OF ELECTRONS IN GATE-DEFINED GaS/Al$_x$Ga$_{1-x}$As QUANTUM DOTS

Dr. Dharmendra Kr. Singh
Deptt. Of Physics
J. P. University, Chapra

ABSTRACT

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 $C_0$ according to $E_c = e^2/C_0$. The temperature of the charge carriers within the 2DEG must be kept below a certain value, namely $K T$, so that the thermal energy of the electrons does not exceed the charging energy $E_c$ of the dot. Keeping the temperature below the $K T$ 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 $C_0$ Since $C_0$ 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.

KEY WORDS: Charging energy, Dimension of the quantum, $E_c$.

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 microwave Here, 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.

EXPLANATION

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 $C_0$ according to $E_c = e' / C_0$. The temperature of the charge carriers within the 2DEG must be kept below a certain value, namely $K_T$, so that the thermal energy of the electrons does not exceed the charging energy $E_c$ of the dot. Keeping the temperature below the $K_T$ 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 $C_0$. Since $C_0$ 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 2DEG 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/Al, Ga As heterostructure.
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 AIGAAS 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 AIGAAS 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 AIGaAs 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, $H \sim 10^{-10}$ cm²/v/s, and long mean free paths, $I 1-1000$ 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.

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 $G > e/h$,
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, $G < \frac{e'}{h}$, 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 $V_{ad}$, the chemical potentials of source $\mu_s$ and drain $\mu_d$, the charging energy $E_C$ and the thermal energy of charge carriers $K_T$. For the conductance measurement a small source-drain voltage $V_{et}$ which is typically limited to be less than a few uV 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 $\delta \mu = \mu_s - \mu_d$. 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

$$E_C = C_{d} \alpha T$$

Here $C_d$ is the self-capacitance of the quantum dot. At temperature $T$ an electron has the thermal energy $K_T$. 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 ($1.e.E > K_T$).
A single photon detector based on coupled double quantum dots

The quantum energy levels as well as the level spacing $\Delta$ 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 $E_{c}/2C$. 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/Alo$_{24}$Ga$_{76}$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 5000Å thick GaAs buffer layer, a non-inverted heterostructure (500 Å thick GaAs/140 Å thick Alo$_{24}$Ga$_{76}$As), a o-doped barrier layer (250 Å thick Alo$_{24}$Ga$_{76}$As), and a o-doped GaAs cap layer (10 Å thick). The silicon n-type dopants (level 6x10$^{13}$/cm) provide the excess charge carriers (target value was 6x10$^{13}$/cm 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-H,O. Finally it was dried by blowing dry N, gas.

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

The resulting Rc resistances for each contact are on the order of tens of k. at room temperature and decrease to a value on the order of ko 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 ko 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 Hal measurements reported in this chapter were taken on a 50 pm wide Hall bar with a 700 am 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 St,N (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 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 torentz 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 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 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. 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, the 2DEG charge carrier density \( n \) was estimated to be about 5.0 \( \times \) 10\(^7\) charges/cm\(^2\) while the charge carrier mobility was estimated to be about 3.0 \( \times \) 10 cm V/s. These two parameters were then used to obtain for example the Fermi Energy \( E \), mean free path Fermi wavelength \( \lambda \), and effective mass \( m \).
REFERENCES