行政院國家科學委員會補助專題研究計畫期中報告

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計畫編號：NSC98－2221－E－009－175 - MY2

執行期間：　98 年　08 月　01 日至 100 年　7 月　31 日

計畫主持人：林聖迪

共同主持人：無

計畫參與人員：巫朝陽 林仕偉

執行單位：交通大學電子工程系

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量子點的傳輸特性與其元件應用

“Transport Property and Device Application of Quantum Dots”

計畫編號：NSC98-2221-E-009-175-MY2

執行期間：98 年 08 月 01 日 至 100 年 07 月 31 日

主持人：林聖迪 交通大學電子工程系副教授

一、中文摘要

在此為期兩年的計劃中，我們進行自組式量子點的傳輸特性與其元件應用的相關研究，不同於一般使用光學激發與偵測來研究量子點的方法，電容與電流的量測能提供單一載子元件應用所需的資訊。在第一年中，我們利用一倒置的高電子遷移率電晶體(inverted high electron mobility transistor)，來探討電子在量子點周圍被捕捉與逃逸的動力學；基於先前對負微分電容的觀測與模擬，我們使用量子點儲存電荷狀態來製作記憶體元件，由於量子點的充電狀態會決定下方二維通道的電導率，所以量測該元件的汲極源極電流可以讀取其記憶狀態；我們利用分子束磊晶成長所設計的結構並設計了各種閘極長度的光罩，完成了元件製作後，量測發現該元件基本電晶體特性完整，而且在特定偏壓下，具有之前所觀察到的電容與頻率的相依特性，顯示我們已達到初期設定的目標。

I. Abstract

In this two-year project, the transport properties of self-assembled quantum dots (QDs) and their device applications will be investigated. Unlike the conventional method using optical excitation and detection to study the QDs, capacitance and current measurements provide the information to unipolar device applications. With an inverted-HEMT structure, the capture and escape dynamic of electrons around QDs have been be studied. Based on our previous observation and modeling of the negative differential capacitance, we fabricated memory devices using QDs as charge reservoir. The memory state can be read out by measuring the source-drain current because the charging state of QDs determines the conductance of the 2D channel underneath. We grew the samples with the designed structure using molecular beam epitaxy method and then prepared the photo mask with various gate lengths. First measurements showed that the basic characteristics of FET were fine. Under certain biases, we observed the frequency-dependent behavior of capacitance as before. It demonstrates that our first goal has been achieved.

二、計畫緣由與目的 (II. Motivation and goal)

In recent years, semiconductor quantum structures have attracted much attention from many excellent research groups, because of their novel properties. One of the most interesting objects is zero dimensional system or so-called quantum dot. Due to the delta-function-like density of states, zero dimensional system is believed to hold unique physical properties. Many theoretical calculations showed that the zero-dimensional system could be implemented to improve the performance of existing semiconductor devices. Many experiments confirmed their points. More recently, many reports predicted that these zero-dimensional (0-D) structures could even have physical properties or functions which can not be provided by conventional materials or devices. Since the InAs/GaAs self-assembled growth of quantum dots was developed in 1990s, we have a way to produce a 0-D system based on semiconductor materials. Very high-quality, nearly defect-free quantum dots have been grown successfully in many groups by using MBE or MOCVD. Devices like quantum-dots lasers or quantum-dot infrared photodetectors (QDIP) were also demonstrated and their performance were promising. To get the most of these self-assembled quantum dots, understandings on their physical properties are essential.

Studies on the quantum states in these

zero-dimensional quantum structures are extensive. One of the major methods is optical characterization like photoluminescence (PL), photoreflectance(PR) and others. The optical way is easy to carry out and important because of their usefulness in optoelectronic device application of quantum dots. When one studies quantum dots with optical pumping, the quantum dots are occupied with both electrons and holes. The interaction between electrons and holes is strong and their physical (or optical) properties are also strongly influenced by the interaction, as revealed in PL results of single quantum dot. However, the physical properties of quantum dots can be very different when they are occupied with only electrons or holes. In the devices using only one kind of carriers (or unipolar devices), e.g., quantum dot infrared photodetectors, these properties are important information for device design and optimization. To study the quantum dots occupying only with electrons or holes, we have to turn to electrical ways instead. Currently, there are two main streams in this direction, current-voltage (I-V) and capacitance-voltage (C-V) characterizations. We shall implement both methods in this two-year project.

三、研究方法及成果 (III. Method and result)

As stated in our proposal, we used an inverted-HEMT structure to fabricate our devices, as shown in figure 1.

i - GaAs 80nm
i – InAs QDs (with or without)
i - GaAs 20nm
i – $Al_{0.33}Ga_{0.67}As$ 10nm
n^+ – $Al_{0.33}Ga_{0.67}As$ 40nm (n^+=2x$10^{18}cm^{-3}$)
i – $Al_{0.33}Ga_{0.67}As$ 300nm
i - GaAs buffer ~200nm
S. I. GaAs substrate

Fig. 1 The sample structure grown by MBE

The 2DEG channel is on the top interface of AlGaAs/GaAs with a 10nm undoped GaAs spacer between the channel and the n-doped AlGaAs carrier supply layer. The QDs layer is 20 nm above the 2DEG channel layer so its charging state can effect the channel conductivity. The samples with QDs (RN0632) and without QDs (RN0633) have both been grown and processed into standard FET devices with various gate lengths, as shown in figure 2.

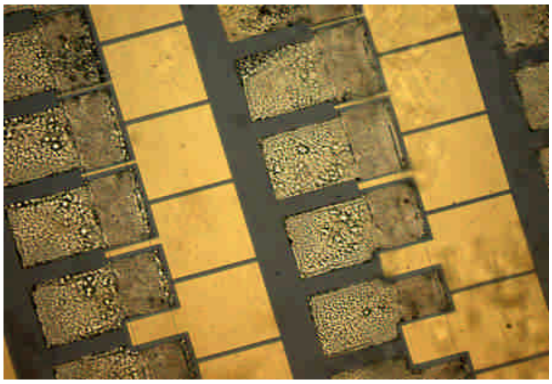

Fig.2 The OM images of finished devices.

To make sure the devices are working well, a three terminal measurement has been performed. The results can be seen in figure 3.

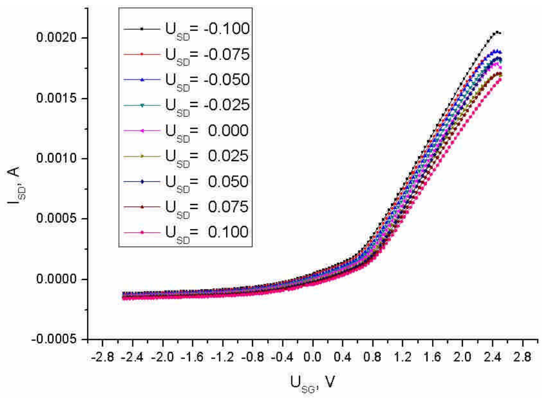

Fig.3 The I-V of the QD-FET devices.

It is clear that the device can be turned off and on properly. The threshold voltage is about –0.5 V. Because this measurement was done with constant voltage/current, we can expect that the QDs were fulfilled with electrons. The QDs charged with electrons are repulsive to the electron in 2D channel, which increases the threshold voltage. In other words, we expect the dynamic threshold voltage is less than –0.5 V. To see this, the C-V measurement was carried out at room temperature in the frequency range from 0.2 to 20 kHz. The capacitance-voltage characteristics were obtained between source and gate with a small AC signal (20mV in amplitude) over DC bias voltages. Figure 4 shows the typical results.

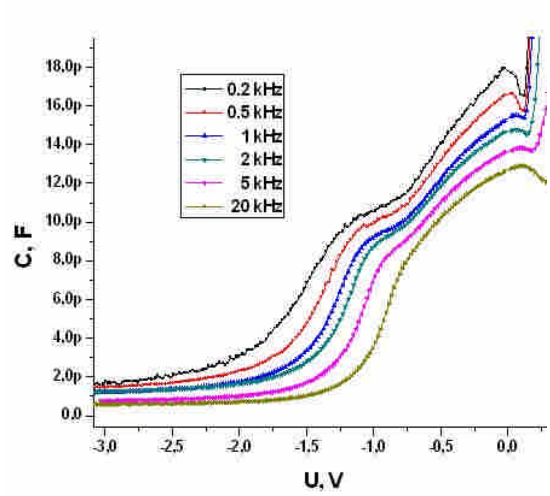

Fig.4 The measured C-V curves at various frequencies.

A careful look will see that the signal around –1.0 ~ -1.5 V is dependent on the testing frequency, which is the typical characteristics of QDs observed in our previous paper. It is worth noting that the frequency-dependent signal in figure 4 is not observed in the sample without QDs. A crucial measurement of the memory device is the pulsed gate voltage read/write operation. However, as our budget for purchasing the pulsed current/voltage source has to wait till the second year, we used an alternative method to see the memory effect. The measurement setup is illustrated schematically in figure 5a. A DC bias accompanying with a small AC signal is applied to the gate contact. The source-drain current is amplified and input into an oscilloscope and recorded.

The amplified source-drain current is plotted against the gate voltage in figure 5b. It is evident that the signal has peaks around –1 to –1.2 V for the testing frequencies from 1 to 150 kHz. As the frequency reduces, the peak value goes higher. Because the lower frequency gives more time to charge the QDs, the conductivity of 2D channel has a significant in-phase change. Therefore, we can see that the charge of QDs do effect the 2D channel as we expected.

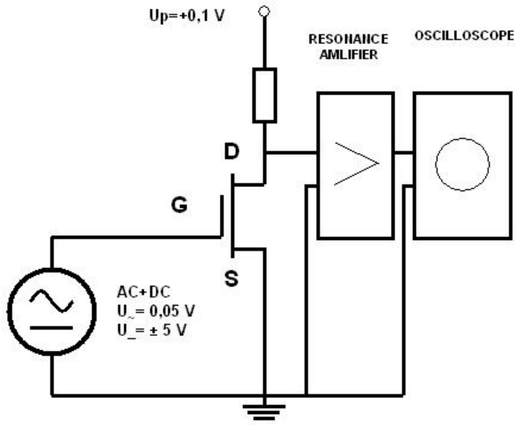

Fig. 5a The measurement setup for QDs memory effect.

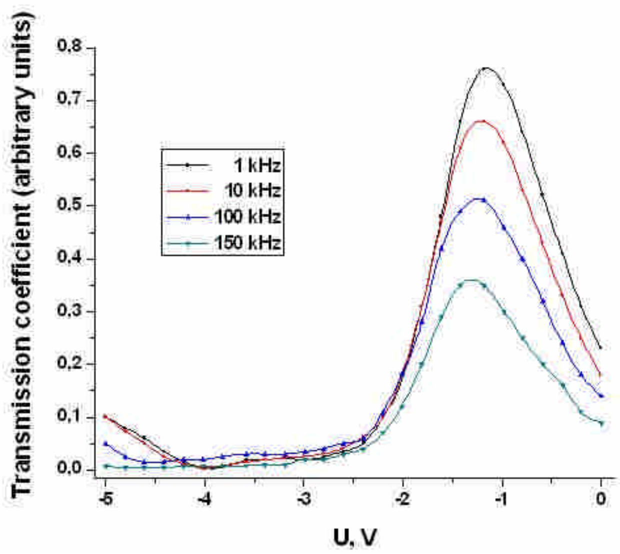

Fig. 5b The data measured with various testing frequencies.

In the rest of this year and next year, we shall test the memory effect in more detail and, based on the first-year results, evaluate the possibility of using the structure in infrared photodetector. We shall also use sub-wavelength grating structure to enhance the absorption in the infrared regime.