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OPTICAL AND ELECTRICAL INVESTIGATION OF LOW DIMENSIONAL SELF-ASSEMBLED InAs QUANTUM DOT FIELD EFFECT TRANSISTORS

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Self-assembled InAs QD dot-in-a-well (DWELL) structures were grown on GaAs substrate by MBE system, and heterojunction modulation-doped field effect transistor (MODFET) was fabricated. The optical properties of the samples show that the photoluminescence of InAs/GaAs self-assembled quantum dot (SAQD) is at 1.265 μm at 300 K. The temperature-dependence of the abnormal redshift of InAs SAQD wavelength with the increasing temperature was observed, which is closely related with the inhomogeneous size distribution of the InAs quantum dot. According to the electrical measurement, high electric field current–voltage characteristic of the MODFET device were obtained. The embedded InAs QD of the samples can be regard as scattering centers to the vicinity of the channel electrons. The transport property of the electrons in GaAs channel will be modulated by the QD due to the Coulomb interaction. It has been proposed that a MODFET embedded with InAs QDs presents a novel type of field effect photon detector.

Keywords: InAs quantum dot; photoluminescence; modulation-doped; field effect transistor.

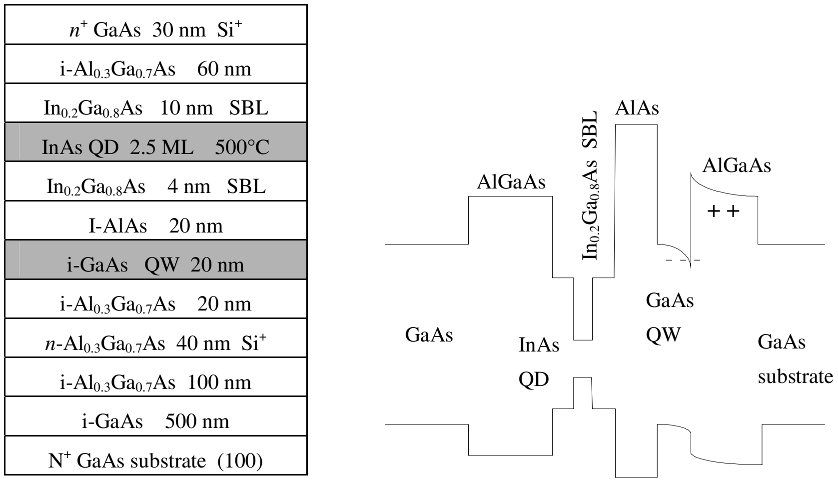
1. Introduction

Low dimensional self-assembled quantum dots (SAQD) have attracted much attention in recent years for their peculiar electronic and optical properties from the point of view of fundamental physics and technological applications on nanodevices. Over last decade, intensive investigations have been focused on the applications InAs/GaAs SAQD as QD laser,[1,2] optical memory,[3] optical detector.[4–6] With the development of crystal growth technology, the Stranski–Krastanow (SK) growth mode in heteroepitaxial system has been proposed as a promising way for fabricating high quality InAs quantum dot in GaAs by MBE. However, the inherent problems of this SK growth mode are the size nonuniformity and the lack of control of the QD position, which may deteriorate the properties of the QD devices. For increasing the InAs QD quality, the growth approach of depositing InAs 3D islands directly on InGaAs strained buffer layer (SBL), so-called dot-in-a-well (DWELL) structure,[7–9] has been widely used to optimize the PL properties and extend the emission wavelength of InAs/GaAs QDs to an important telecommunication wavelength of 1.3 μm.

In this work, optical and electrical properties of InAs/GaAs DWELL modulation doped field effect transistors (MODFET) were investigated. The emission wavelength of the sample is around 1.3 μm at room temperature. The temperature dependence of the abnormal shift of InAs QD wavelength was observed. A heterostructure MODFET device embedded with InAs QD was fabricated by standard post-growth processing, and the current–voltage (*I*–*V*) characteristics, which can resist high gate-voltage, were observed at room temperature.

2. Structure and Process

Figure 1 shows the schematic layer structure and energy band diagram of the samples, which were grown on n^+ GaAs(100) substrates by MBE system. This structure mainly consists of two parts: an $Al_{0.3}Ga_{0.7}As$/GaAs heterojunction for a conventional MODFET, and an embedded InAs/GaAs nanodots DWELL at the vicinity of the MOD conduction channel. To be specific, after a 500 nm thick GaAs buffer layer was deposited on the GaAs substrate, a modulation structures were successively grown with a 100 nm undoped $Al_{0.3}Ga_{0.7}As$/GaAs, a 40 nm Si^+-doping ($1 \times 10^{18} cm^{-3}$) $Al_{0.3}Ga_{0.7}As$ layer, a 20 nm spacer layer of undoped $Al_{0.3}Ga_{0.7}As$, then a 20 nm GaAs quantum well was grown as the two dimension electron gas (2DEG) channel. Whereafter a 20 nm broad band AlAs layer was deposited as a barrier layer. Then a DWELL structure was grown with 4 nm $In_{0.2}Ga_{0.8}As$ strain buffer layer (SBL), 2.5 ML InAs quantum dots layer, 10 nm $In_{0.2}Ga_{0.8}As$ upper SBL. Followed by a 60 nm-undoped $Al_{0.3}Ga_{0.7}As$ capping layer, and finally 30 nm n^+ ($3 \times 10^{18} cm^{-3}$) GaAs Ohmic contact layer. Most of the wafer structures were grown at a nominal growth temperature of 600°C, except that of the InAs quantum dot layer was at 500°C.



(a) (b)

Fig. 1. (a) Schematic diagrams of QD-DWELL structure and (b) energy-band structure of the QD MODFET.

The photoluminescence (PL) measurement was performed by using a variable temperature (10–300 K) closed-cycle cryostat on Nicolet760 FTIR system. The He–Ne laser (632.8 nm) with the power of 15 mW was used as the excitation light source. The signal from the sample was detected by a cooled Ge detector.

The wafers were formed into MODFET devices by using standard photolithography process. A narrow mesa (5 × 20 μm) with embedded InAs/GaAs quantum dot was isolated from the source and drain regions by wetting etch (shown as Fig. 6). The standard source and drain AuGeNi Ohmic contacts were made to the either ends of MODFET electron channel. A nominal semitransparent Au Schottky gate was deposited upon the center of the mesa, varying from the length of the gate, 5 μm and 10 μm, respectively. The current–voltage (*I*–*V*) measurements of the MODFET were performed on the HP 4140B PA meter.

3. Results and Discussion

3.1. *PL characteristics of InAs DWELL*

Figure 2 shows the temperature dependence of the PL spectra from self-assembled InAs quantum dots wafer. The PL curves of InAs QDs take the well-shaped Gaussian-like distribution under the low temperature. The full wide at half maximum (FWHM) of the PL spectra is around 60 meV at 10 K, indicating the optical properties of InAs QD. The emission peak of InAs QD gradually red-shifts with the increasing of the temperature from 1.159 μm at 10 K to 1.265 μm at 300 K. No excitation states emission was observed in PL spectra under the excitation power of 15 mW in this work.

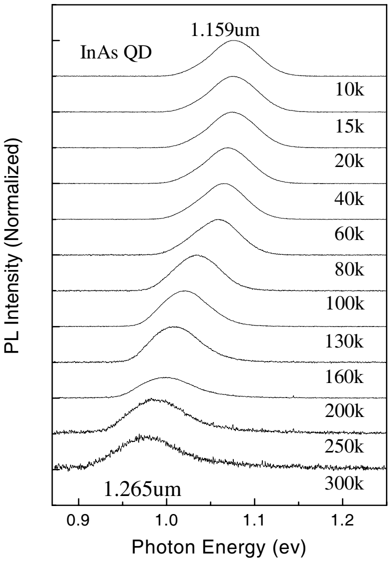


Fig. 2. PL of InAs QD at different temperature (λ: 1.159–1.265 μm).

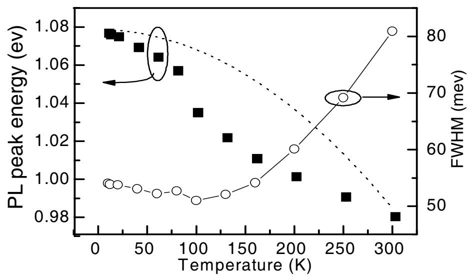


Fig. 3. Temperature dependence of InAs QD PL peak energy and FWHM.

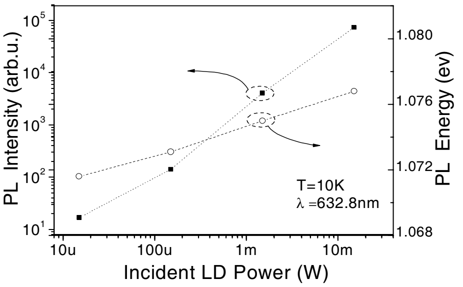


Fig. 4. LD power dependence of InAs QD PL intensity and peak energy.

In more detail, the temperature dependence of InAs QD PL peak energy and FWHM are shown in Fig. 3. The FWHM of the InAs QDs drops slightly at low temperature and then increases steeply when it is above 100 K (shown as open circle). This thermal effect can be explained as more photogenerated carriers, which locate at the different energy levels of QDs, participate in the radiative recombination at high temperature, thus result in the broading of the FWHM. Moreover, the redshift of InAs QD PL energy peak with increasing temperature is much faster than that of the band gap of bulk InAs. This feature can be clearly seen in the figure, where the solid squares represent the experiment data and the dotted line, which is simulated by Varshni's semi-empirical function,[10] represents the band edge shift of the InAs bulk with temperature. A similar phenomenon was found by Xu *et al.*,[10] and was explained with the relaxation effect and thermal activation process of the excitons. To be specific in this work, the abnormal redshift of InAs DWELL QD with increasing temperature is closely related with the size fluctuation of the quantum dots. The thickness of 2.5 ML InAs QD is greater than the critical thickness of 1.7 ML,[11] which result in the high-density QD system and large dots size. In other words, the distance between the adjacent dots is rather small in large size QD cluster, so the electron wave functions at respective dots will extend to the lateral direction and couple with that of other electrons, hence the photogenerated carriers move from small dots to large ones via tunneling, and recombine there taking the lower energy states in large size dots. Therefore the fast redshift of InAs QD PL peak energy occurs at the given temperature regions.

Figure 4 shows the LD (632.8 nm) excitation power dependence of InAs QD PL intensity and peak energy. The solid squares represent the PL intensity as the function of the LD excitation power varying from 15 μW to 15 mW. Although no emission from excitation states of InAs QD was observed, even at the highest power density of 15 mW in this work. However the blue shift of ground states from InAs QD is indicated with the increasing of the excitation power. Actually, as the excitation power increasing, the ground states of large dots are occupied by photogenerated carriers and then further carriers will transfer to the higher potential levels in the cluster of small dots. Therefore, the recombination of carriers from small dots become predominated, thus result in the blue shift of the PL peak energy with the increasing of the power density. In a word, the dot size-dependent excitation plays an important role in the PL characteristic of the InAs quantum dots devices.

3.2. *I–V characteristics of InAs QD MODFET*

In Fig. 5, we illustrate a schematic device structure and Fig. 6 shows the SEM image of MODFET embedded with InAs QDs. The wide and length of the active region mesa are 5 μm and 20 μm, respectively. Figure 7 reveals the *I–V* characteristic of InAs QD MODFET device with 5 μm length gate measured at room temperature. This device is similar to conventional *n*-channel normally on (depletion type) field effect transistor, because the saturated current is still on (around 60 μA) even when the $V_g = 0$ V. Well-ordered *I–V* curves were obtained with the positive and the negative gate bias with the voltage step of 0.2 V/step, while the negative gate bias can modulate the channel current move effectively. The inset in Fig. 7 shows the transfer characteristic curve of the device at $V_{DS} = 6$ V and the pinch off voltage V_p is around – 10 V. The transconductance of the devices g_m is about 1 ms/mm. Two notable phenomena, i.e., the high gate voltage–resistance and the low transconductance in this work, may result from the existence of the InAs QD embedded in the devices.

The output characteristics of the MODFET with embedded InAs QD are controlled by (1) the transport through the channel layer in the 2DEG of MOD layer. (2) the coulomb interaction between the 2DEG and the QDs.[12] In this work, the embedded self-assembled InAs QDs can be regard as scattering centers to the vicinity of 2DEG in MODFET structure. For one thing, the excess electrons captured in QDs can weaken the modulated effect of the 2DEG from the upper metal gate, which result in the abovementioned two phenomena. For another, the InAs QDs can resonate to the incident near infrared light and thus may significantly influence the output property of the MODFET due to the Coulomb scattering from the photogenerated carriers. Therefore, it

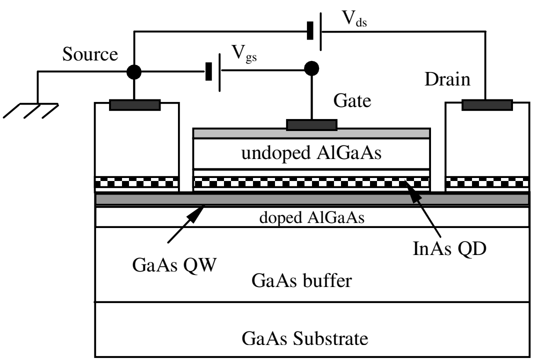


Fig. 5. Schematic structure of QD-MODFET.

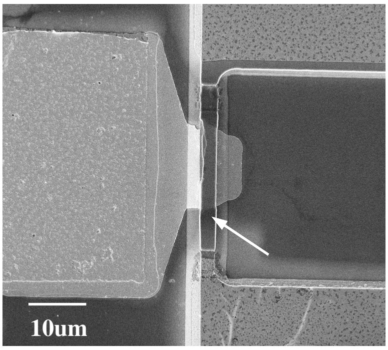


Fig. 6. SEM image of InAs QD-MODFET.

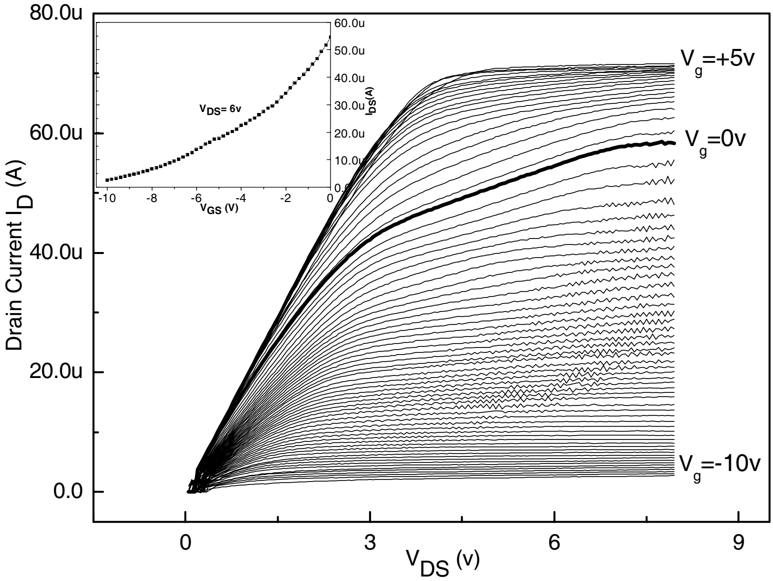


Fig. 7. Current–voltage characteristic of the InAs QD-DWELL MODFET measured at RT. The inset figure shows the transfer characteristic curve of the device at V_{DS} = 6V.

has been proposed that this MODFET structure embedded with InAs QDs presents a novel type of field effect photon detector. This ongoing work needs further intensive investigation and we will report it elsewhere.

4. Conclusions

In conclusion, we have investigated the optical properties of dot-in-a-well (DWELL) self-assembled InAs quantum dots (QDs), whose photoluminescence (PL) wavelength reach around 1.265 μm at room temperature. The abnormal redshift of the PL peak of InAs QDs with the increasing of the temperature is closely related with the inhomogeneous size distribution of the QD in high density QD system. A heterostructure modulation doped field effect transistor (MODFET) with embedded InAs QDs was fabricated, and high gate voltage–resistance *I–V* characteristics of the device were observed. It has been proposed that a MODFET embedded with InAs QDs presents a novel type of field effect photon detector in the near future.

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