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Application of Wet Chemical Etching in Fabrication Process of GaAs/AlGaAs Quantum Dot Arrays

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Abstract Two types of GaAs/AlGaAs quantum dot arrays with different dot size are fabricated by dry etching and dry-wet etching. PL spectra of the quantum dot arrays at low temperature show the blue shifts due to the quantization confinement effects, and the blue-shift increases with the decrease of the dot size. It is also found that wet chemical etching can reduce the surface damage caused by high-energy ion etching and improve the optical characteristics of the quantum dot arrays.

Key Words: Quantum Dot, Arrays, Chemical Etching
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1 Introduction

Low dimensional structures, such as quantum well (QW), quantum wire (QWR) and quantum dot (QD) have attracted more and more attention in recent years[1]. Both the fabrication technologies of low dimensional structures and their fundamental optoelectronic properties have become active subjects in frontier.

There are various methods of fabricating QDs, such as the conventional epitaxial growth, chemical crystallization and so on. In addition, QD arrays can also be fabricated by etching method[2,3]. The low dimensional structures fabricated by etching have been seldom reported in China by now. In recent years, many authors[4~11] are devoting themslves to the investigation of the QDs made by self-organization epitaxial growth and their optical and electrical properties.

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Using the etching method, QD arrays based on QW wafers are fabricated by electron beam lithography (EBL), reactive ion etching (RIE) and wet chemical etching. Patterns of the QD arrays made in this way are reproducible well and the dot sizes are more homogenous. During the process of the reactive ion etching, however, high-energy ion increases the surface damage at open sidewalls of the dots. If wet chemical etching were adopted after the reactive ion etching, the surface damage would be reduced and the qualities of QD arrays can be improved greatly.

2 Fabrication of Quantum Dot Arrays

Two types of GaAs/$Al_xGa_{1-x}As$ quantum well structures, samples No. 702 and No. 706, in this work are grown by Molecular Beam Epitaxy (MBE). Their structures are very similar. Structure of Sample No. 702 in figure 1(a) is as follows:

The substrate is a Si doped n^+-GaAs with Si density of $2\times10^{18}\,cm^{-3}$. After growing a GaAs buffer layer (1μm), the following layers were grown successively: 1) 400 nm first $Al_xGa_{1-x}As$ barrier layer, 2) 6 nm GaAs quantum well, 3) 2 nm $Al_xGa_{1-x}As$ barrier layer, 4) a second 6 nm GaAs quantum well, 5) 150 nm $Al_xGa_{1-x}As$ barrier layer, 6) 100 nm GaAs top cover layer. All the epitaxial layers are undoped and Al composition value in $Al_xGa_{1-x}As$ layers is 0.3.

The fabrication of QD arrays is expressed by the following processes:

Resist on the wafer surface → EBL → development → evaporation of NiCr alloy and metallization → lift-off → RIE → (wet chemical etching) → cylindrical quantum dots.

For sample No. 702, two kinds of QD arrays with dot diameter of 100 nm and 50 nm, respectively, were successfully fabricated. The double GaAs quantum dots with the thickness of 6 nm were sandwiched between $Al_xGa_{1-x}As$ barrier layers.

Another sample No. 706 was also investigated in order to identify the function of the wet chemical etching in the processes. The sample structures and the qualities are similar to those of No. 702. Sample No. 706 with double GaAs QWs was grown by MBE, as shown in Fig. 1(b). The thicknesses of the double wells are 4.2nm and 19.5nm, respectively. The double QWs

GaAs	100 nm
AlGaAs	150 nm
GaAs	6 nm
AlGaAs	2 nm
GaAs	6 nm
AlGaAs	400 nm
GaAs buffer	~ 1 μm
n^+-GaAs substrate	

(a) No. 702

GaAs	70 nm
AlGaAs	86.5 nm
GaAs	19.5 nm
AlGaAs	30 nm
GaAs	4.2 nm
AlGaAs	86.5 nm
GaAs buffer	300 nm
n^+-GaAs substrate	

(b) No. 706

FIG. 1 Structures of MBE-Grown QWs

were defined by three $Al_xGa_{1-x}As$ barrier layers. Three kinds of QD arrays were fabricated on sample No. 706's wafer, with the diameters of QD dots formed after RIE being 130nm, 75nm and 46nm, respectively.

For the No. 702 and No. 706 sample, the qualities and structures are almost same, but their fabrication processes are rathes different: after RIE process, wet chemical etching was applied for sample No. 702, while the QD arrays on sample No. 706 were only made by dry etching but never treated by wet chemical etching. The difference between QD arrays by dry etching and by dry-wet etching is obvions and comparable. In next section, the effects of wet chemical etching on the optical properties of QD arrays could be found from the measured PL spectra.

3 Results and Discussion

PL properties of QD arrays as well as of the relative QWs were investigated at low temperatures. An Argon ion laser was used as an excitation light source and PL spectra of QD arrays were shown in Fig. 2. At the same time, PL spectra of MBE-grown QWs were measured as a reference. Comparing the PL spectra of the QD arrays with those of the reference QWs, we obtained the following results:

(1) Blue Shift

As shown in Fig. 2(a), PL spectrum of the reference QW has a very strong and narrow luminescence peak, whose energy position is at 1.6050 eV and full width at half maximum (FWHM) is 5 meV. PL spectra of the two quantum dot arrays, QD-100 nm and QD-50 nm, have distinct emission peaks. In comparison with the reference PL, the peak positions of the QD arrays shift towards the higher energy and the blue-shift is 2.5 meV and 5.5 meV, respectively. It is primarily due to the quantum size effects: electrons and holes in a QD are confined at three directions. The lateral confinement leads to the heightening of carrier subband, thus the blue-shifts of the emission peaks from the QD arrays are observed. The smaller the diameter of the QD would be the stronger the lateral confinement effect and the larger the blue-shift[2,12] are.

Besides, we have estimate the rough theoretical value of the blue-shift. The peak energy emitted from QW and QD was calculated by a simplified model and compared with the experimental results provided it is a single QD and the barriers are infinite, the well-known energy expression could be given as follows:

$$E = \frac{\hbar^2\pi^2}{2m_e^*}\left[\left(\frac{n}{L_z}\right)^2 + \left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2\right] \tag{1}$$

For sample No. 702, the shifts of the PL position of QD, comparing with the reference PL, are 2.2 meV and 6.1 meV for QD-100 nm and QD-50 nm, respectively. The calculated values coincide with the experimental data very well. It indicates that the experimental data are reasonable and trustworthy.

(2) Broadening PL Peak

The PL peaks of the two QD arrays are broadened till the FWHMs are 11meV and 7meV, respectively. This is caused by the fluctuation of the dot sizes. The quantum dot are not very homogenous, so the increment of the linewidth should be explained as the combined emission from the dots with slightly different sizes.

(3) Weakening PL Intensities

The PL intensities of two QD arrays are weakened. On the one hand, the reason can be explained as that in QD arrays, the area excited by Ar^+ laser is much smaller than that in QW, so the shrinkage of the illumination area leads to the weakening of PL intensity; on the other hand, the decrease of PL intensities may be attributed to the influence of non-radiative recombination via the surface states and faults on the open sidewalls.

PL spectra of No. 706 measured at 10 K are shown in Fig. 2(b). The peak energy and the FWHM of QW with 19.5 nm well thickness are 1.5492 eV and 3 meV, respectively. It is similar to those of No. 702, the blue-shifts of the three QD arrays (QD-130 nm, QD-75 nm and QD-46 nm) are 2.0 meV, 2.7 meV and 4.3 meV, respectively. The PL intensities are greatly weakened and their low energy sides are broadened enormously. The FWHMs are about 50~ 60 meV.

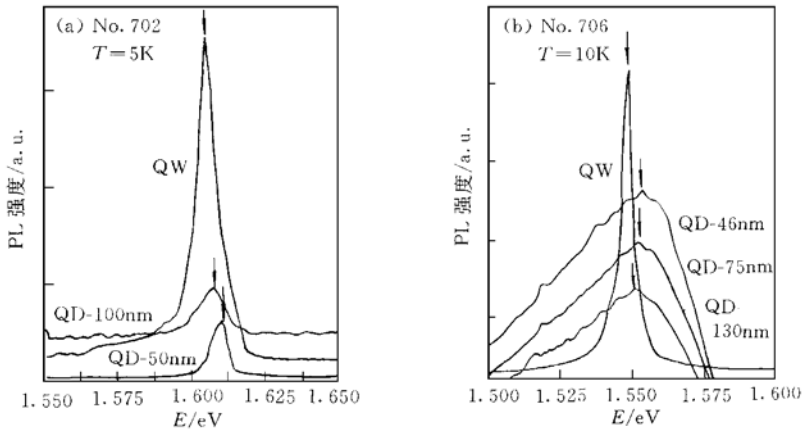

FIG. 2 PL Spectra of QD Arrays with Different Dot Diameters and the Reference QWs

(4) Advantage of Wet Chemical Etching

As mentioned above, the structures of samples No. 702 and 706 are similar. But why their PL peak linewidth of the QD arrays are so different? The increment of linewidth of the emission spectra is caused by the fluctuations of the dot size. In fact, only dot-sized fluctuations exist within a quantum dot array. Therefore, the main reason is that the reactive ion etching causes a lot of surface damages on the open sidewalls of the dots. The surface states locate usually under the conduction band and above the vacancy band. All in all due to the influence of recombination via the surface states and faults, the PL intensities

are greatly reduced and the PL peaks are widened enormously. It indicates that the application of wet chemical etching after reactive ion etching in fabrication processes is very necessary and valid to decsease the surface damage.

Among three QD arrays in sample No. 706, the luminescence signal from QDs with well thickness of 4.2 nm was too weak to detect.

It should be pointed out that the QD arrays can also be fabricated directly by wet chemical etching after lift-off without using reactive ion etching. From PL spectra of the QD arrays, it is found that the surface damage at the open sidewalls is decreased greatly. The peak becomes very sharp. However, it is difficult to make the size of the quantum dots small because of isotropy of the chemical etching solution, so the confinement effects in the emission spectra are not quite evident. Therefore, it is important to find an ideal anisotropy solution.

4 Conclusion

In this paper, the QD arrays were fabricated by combining MBE growth with microfabrication techniques together. In comparison with the reference PL the PL peak positions of the QD arrays shift to a higher energy side, whether using wet chemical etching or not in fabrication processes. The blue-shift amounts observed in experiment are in agreement with the theoretical values calculated by a simplified model. The smaller the dot size is, the larger the blue-shift will be. The blue-shifts can be attributed to the lateral quantization size effects.

Wet chemical etching plays an important role in the fabrication of the QD arrays. The technology can not only smooth the sample surface, but also reduce the surface damage caused by high-energy ions. Thus it improves the optical properties of the QD arrays. Although the structures and qualities of the samples are very similar, their PL peak shapes are quite different.

High quality of QDs makes it possible to develop and applicate those optoelectronic devices. It expected that the PL characteristics of QDs will be improved dramatically by many ways, such as increasing the resolution of electron beam lithography, enhancing the dot density and homogeneity, using low-energy reactive ion etching and wet chemical etching, etc.

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