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Effects of growth interruption on self-assembled InAs/GaAs islands

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Abstract

The effect of growth interruption on the InAs deposition and its subsequent growth as self-assembled island structures, in particular the material transport process of the InAs layers has been investigated by photoluminescence and transmission electron microscopy measurements. InAs material in structures with only coherent islands transfers from the wetting layer to the formed islands and the growth interruption causes a red shift of PL peak energy. On the other hand, the PL peak shifts to higher energy in structures containing simultaneously coherent and noncoherent islands with dislocations. In this case, the noncoherent islands capture InAs material from the surrounding wetting layer as well as coherent islands, which casues a reduction in the size of these islands. The variations in the PL intensity and line width are also discussed. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Coherent island growth on GaAs(1 0 0) at the earliest stages of InAs deposition provides a promising technique for fabricating optically efficient three-dimensional confined quantum dots (QDs). When the thickness of the InAs layer increases beyond the transition thickness around 1.7 monolayer (ML), layer-by-layer growth changes to strain-induced islanding, which is known as the Stranski–Krastanov growth mode. As these islands of small size occur spontaneously, they are often refereed to as self-assembled QDs. Their typical dimensions are: base ∼10 nm and height 5 nm with a deviation about 10–20%. The size

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distribution was found to depend strongly on the growth conditions [1,2], and this has hindered their application in optoelectronic devices. A lot of effort has been made to make islands more coherent and uniform in size, such as optimizing substrate temperature, V/III ratio, and growth rate. However, no obvious systematic improvement has been observed. Increasing uniformity in both spacing and size has been predicted in vertical correlated multilayer island structures [3]. Postgrowth annealing treatment could narrow the luminescence line width [4], which has been reported very recently and was attributed to a homogenization of island sizes. To establish whether it is possible to obtain sufficiently uniform islands for practical applications requires more study of the dynamics of island formation.

In this communication, we have investigated the development of photoluminescence (PL) spectra for different time growth interruptions, which were introduced, between the InAs deposition and its subsequent growth of the upper GaAs layer. The PL peak of 1.7 ML island structure shifts to lower energy, and similar behavior has been reported by Gerard [5] and Heinrichsdoff [6]. On the other hand, the introduction of growth interruption induces a blue shift of the PL peak and a decrease of the intensity for 3.0 ML island structures. The PL spectra variance implies a material transfer process in these structures. Transmission electron microscopy (TEM) image shows that coherent and noncoherent islands simultaneously appear in the 3.0 ML island structures.

2. Experimental procedure

2.1. General

The structures studied here were grown by molecular beam epitaxy using a VG V80H-MKII system. The substrates used were semi-insulation (1 0 0)GaAs. Growth rates were 1 μm/h for GaAs and 0.1 μm/h for InAs. A 1 μm GaAs buffer layer was deposited first at 600°C, followed by a single InAs layer, with 1.7 or 3.0 ML coverage, at 450°C. And then a period of growth interruption for different time was introduced before a 20 nm GaAs cap layer was grown to complete the structures. The formation of islands was verified by the reflection high-energy electron diffraction (RHEED) patterns change from streak-like to spot-like and also by scanning tunneling microscopy (STM) measurement [7,8].

The PL measurement was performed at a close-cycle cryostat maintained at 12 K under the excitation of a 514.5 nm line of an argon laser. The signal from samples was detected by a cooled Ge detector. TEM images were observed by Phillips CM200 FEG microscopy.

2.2. Island structures from ~1.7 ML InAs deposition

The luminescence spectra from 1.7 ML island structures without and with growth interruption are shown in Fig. 1. The PL peak red-shifts about 70 meV after a period interruption for 20 s. It is well established that the initial InAs layer obtained by the continuous growth on GaAs substrate is in an unstable state [9]. The InAs islands grow in size at the expense of the surrounding InAs wetting layer during the period of growth interruption. It has been reported that the InAs layer would reach a quasi-equilibrium state within 20 s [5].

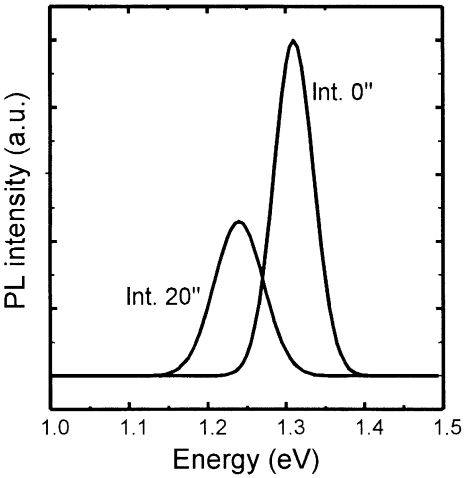

Fig. 1. PL spectra of 1.7 ML InAs/GaAs island structures without and with growth interruption after growth of InAs.

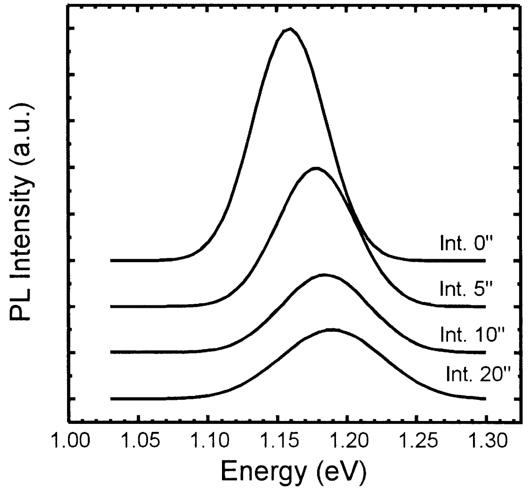

Fig. 2. PL spectra of 3.0 ML InAs/GaAs island structures with different growth interruption times.

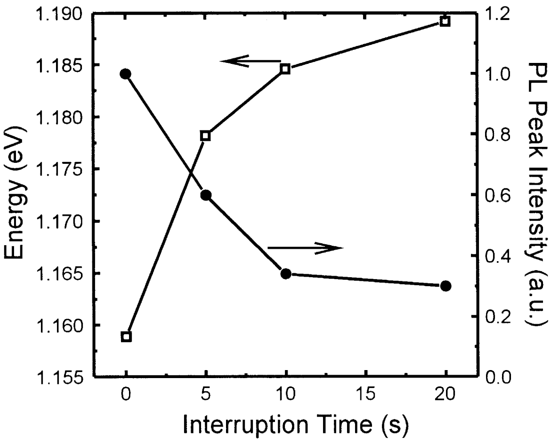

Fig. 3. PL peak energy and intensity of 3.0 ML InAs/GaAs island structures as a function of growth interruption time.

2.3. Island structures from ∼3.0 ML InAs deposition

Fig. 2 shows the PL spectra of 3.0 ML InAs/GaAs structures grown using different growth interruption periods. By introducing growth interruptions ranging from 0 to 20 s, the PL spectra can be changed significantly in spectral peak position, intensity and line width, as shown in Figs. 3 and 4.

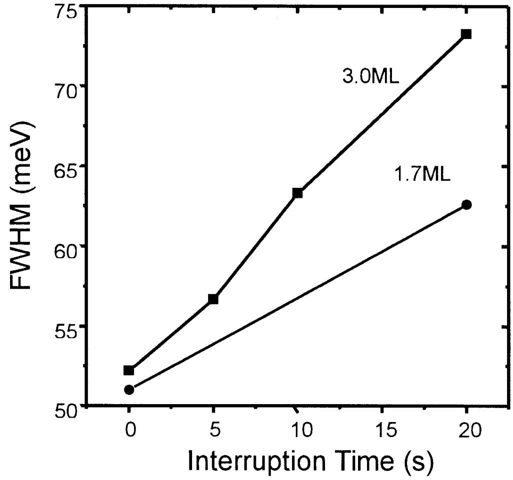

Fig. 4. PL linewidth of 1.7 ML and 3.0 ML InAs/GaAs island structures with different growth interruption times.

In contrast with that of 1.7 ML structures, PL peak of 3.0 ML structure shifts towards higher energy as a result of growth interruption. The different variance of PL peak could be attributed to the difference in the character of the structures. As is well known, coherent islands first nucleate on top of the wetting layer for growth thickness exceeding the transition thickness. We have obtained dislocation-free islands even in 2.5 ML InAs/GaAs structures as confirmed by TEM and STM measurements [7,8]. By depositing InAs continuously, misfit dislocations form at the edge of large islands. Fig. 5 is a plan-view TEM image of 3.0 ML structure. A large density of coherent islands, about $5\times10^{11}/\mathrm{cm}^2$, is observed. The large islands take various shapes and the observation of moiré patterns indicated the existence of misfit dislocations. The misfit dislocations could relax a large part of strain energy. It was observed that the subsequent deposition of InAs tends to grow quickly in the region containing dislocations. The noncoherent islands with dislocations grow up remarkably while the size of coherent islands changes only slightly [10,11]. Based on these results, we can expect that InAs would transfer towards the noncoherent islands so as to reduce the strain and free energy in the system during the growth interruption. There is a vague blank region where no islands are observed

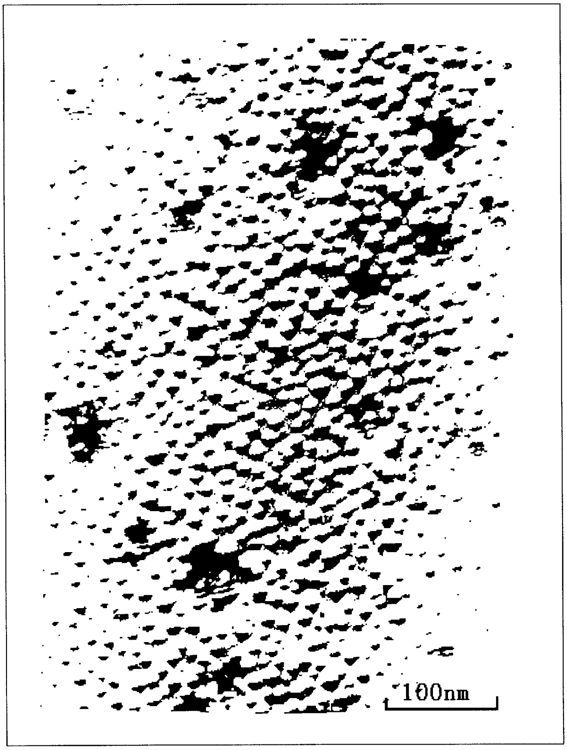

Fig. 5. Plan-view TEM image of 3.0 ML InAs/GaAs island structure without growth interruption.

around some noncoherent islands, which may be a results of InAs material transport. The movement of InAs results in a reduction of the coherent island sizes, which is the origin of the PL peak blue shift. Increasing the period of time for growth interruption causes greater amounts of InAs to accumulate in the noncoherent islands, which results in an increase in the nonradiative centers leading to a decrease of the PL intensity.

3. Discussion

The variational curves of the PL peak energy and intensity give the hint that the changes have the same origin as the generation of misfit dislocations. The material transport associated with dislocations may be the cause of the inhomogeneous distribution of coherent island size corresponding to the broadening of the PL line width. However, the variational tendency of the line width without saturation differs from that of the peak energy and intensity in the 3.0 ML structures. On the other hand, the PL line width of 1.7 ML structures is also increased following growth interruption. Similar behavior has been observed in various InAs/GaAs structures without dislocations by Gerard [12]. It is expected that the larger islands grow more slowly than the smaller islands during growth interruption, leading to a reduction of PL line width, as has been theoretically analyzed by considering the strain concentration near the island edge [13]. Further theoretical and experimental work needs to make clear the origin of the variation in PL line width of the self-assembled island structures with and without misfit dislocations during growth interruption.

4. Summary and conclusions

In summary, we have investigated the material transport of self-assembled InAs islands with 1.7 and 3.0 ML coverage by PL and TEM measurement, monitoring by applying different periods of growth interruption prior to the growth of the GaAs cap layer. For 1.7 ML island structures, the shift of the PL peak towards lower energy has been explained by matter transfer from the wetting layer into the coherent islands leading to an enlargement of these islands. Different from 1.7 ML free-dislocation island structures, some noncoherent islands containing dislocations have been observed in the 3.0 ML island structure by TEM, around which there exists a margin with no islands. This implies that these noncoherent islands behave as traps causing InAs material transport. A reduction of the coherent island size for the 3.0 ML island structure is expected, in agreement with the shift of the PL peak towards higher energies due to the increase of the growth interruption time. For both 1.7 and 3.0 ML islands, the PL line width broadens as a result of introducing the period of the growth interruption. A tentative discussion on that has also been given. We hope that our results will motivate further investigations to obtain more uniform InAs/GaAs island ensemble.

Acknowledgements

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