Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 92-93

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Formation of 1μm-period GaAs Kagome Lattice Structure by Selective Area Metalorganic Vapor Phase Epitaxy

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1. Introduction

Rapid progress in semiconductor nanofabrication technology has enabled to develop structures with novel electronic, optic and magnetic properties. It has also led to various theoretical predictions for novel nanostructures such as artificial molecules and artificial lattice. Such an idea of forming artificial two-dimensional lattice using quantum dots is very promising since any type of lattice structure that cannot be realized in real materials can be designed and various theoretical ideas have been proposed with possible interesting effects. One such semiconductor two-dimensional lattice pattern is Kagome lattice, which is composed of corner-shared triangles. The interesting feature is that it has dispersionless flat band in their single particle band structure. It has been theoretically proved that ferromagnetism appears in such a lattice when the flat band is half-filled [1]. The formation of such an artificial Kagome lattice using quantum dots is very promising since they can replace the magnetic materials which are not compatible with conventional integrated circuit technology. The aim of the present work was to fabricate such a semiconductor Kagome lattice structure.

Recently, Shiraishi et at have proposed the theoretical design of semiconductor Kagome lattice using quantum dots [2]. The structure consisted of crossing quantum wires with square cross-section. In the present work, a similar design was adopted with GaAs quantum wires. SA-MOVPE was utilized to fabricate the Kagome lattice structure. GaAs (111)B was chosen as the substrate since {-110} vertical facets appear during selective area growth and also the three-fold symmetry on the (111)B plane facilitates the growth of triangular and hexagonal structures [3].

2. Experiment

Figure 1 shows the schematic illustration of the pattern of the masked substrate used for the selective area growth. The mask patterns were formed on SiO_2 coated GaAs (111)B substrates by electron beam lithography and wet chemical etching. Kagome lattice patterns were formed with various periods of 3, 1.5 and 1 μm and with wire opening widths ranging from 150 to 70 nm. A horizontal low-pressure MOVPE system was used with trimethylgallium (TMGa), trimethyaluminium (TMAl) and arsine (AsH_3) as source materials. The partial pressure of AsH_3 was $5x10^{-5}$ atm because low As coverage conditions are necessary for MOVPE growth of GaAs (111)B surface. For the growth of GaAs layers the partial pressure of TMGa was $7.3x10^{-7}$ atm and for the AlGaAs barrier layers the partial pressures of TMGa and TMAl were $3.7x10^{-7}$ and $1.2x10^{-6}$ atm respectively.

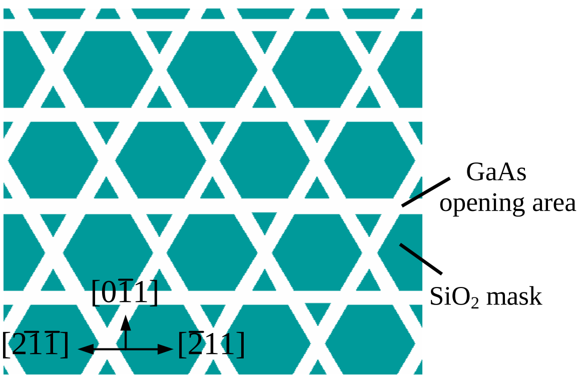

Fig.1 Schematic illustration of mask pattern

GaAs/AlGaAs quantum wells were grown on the masked substrates with the above conditions to form the Kagome lattice structure. The layer structure typically consisted of a 100nm GaAs buffer layer, a 20nm bottom AlGaAs barrier layer, a 10nm GaAs well layer, 20 nm top AlGaAs barrier layer and a 10nm GaAs cap layer.

Apart from conventional MOVPE, growth was also carried out by flow rate modulation epitaxy, which is based on alternate supply of group III and group V sources. It has been proved that FME has a remarkable effect on improving the shape controllability in SA-MOVPE [4]. The flow sequence consisted of alternate TMGa/TMAl and AsH_3 flow with a H_2 purge period in between in order to avoid gas mixing. The gas flow sequences of both the methods are shown in Figure 2.

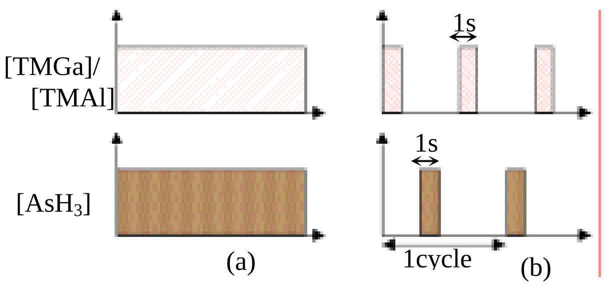

Fig.2 Gas flow sequence of (a) MOVPE (b) FME

The two AlGaAs barrier layers and the GaAs quantum well layer were grown by FME and the GaAs buffer layer and the GaAs capping layer were grown by conventional MOVPE. The growth temperatures for MOVPE and FME were 850 ° and 750°C respectively since higher growth temperature is an essential condition for MOVPE growth on GaAs (111)B plane because As trimers are formed at lower temperature, but in case of FME the growth temperature can be reduced since the As trimers evaporate during the H_2 purge period after AsH_3 flow. Experiments were carried out with different gas flow sequence in order to optimize the growth conditions. The samples were characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM).

3. Results and Discussion

Figure 3(a) shows the scanning electron microscope image of 3μm-period Kagome lattice structure grown by SA-MOVPE. The results indicate that it is possible to realize uniform semiconductor Kagome lattice structure on GaAs (111)B substrate. However, growth on shorter period pattern did not exactly follow the mask pattern and shape deterioration was found to occur due to lateral overgrowth (LOG) on the mask area (Figs. 3b and c).

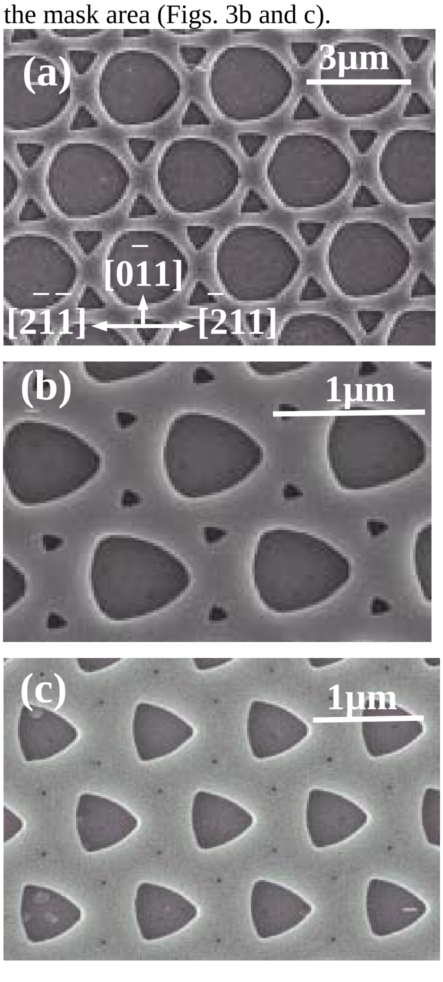

Fig.3 SEM images of (a) 3 (b) 1.5 and (c) 1 μm-period Kagome lattice structure grown by SA-MOVPE

The occurrence of LOG is a serious problem in case of Kagome lattice structure since even a small percentage of LOG will bury the smaller triangular mask area resulting in a completely different pattern. The occurrence of LOG is also due to the pattern shape. In case of Kagome lattice mask pattern, the opening area consists of many corners, which in turn consists of many steps and kinks. During growth, the migrating Ga atoms will be incorporated into these steps and kinks and hence blunting the sharp corners The incorporation probability of Ga is related to the density of the dangling bonds at the step edge, and the dangling bond density is related to the availability of As at the step edge [5]. Hence, low As coverage is essential to ensure that the migrating Ga atoms are not incorporated into steps and kinks at the corners and thereby preventing lateral overgrowth.

Hence, to improve the shape of the smaller period patterns, flow rate modulation epitaxy (FME) was employed. By using FME growth, the shape of the grown layer was found to follow the mask pattern and the edges were found to be sharp, indicating that the migrating Ga atoms are not incorporated into steps and kinks at the concave positions. This is probably because a low As coverage during the TMGa/TMAl supply period in FME prevents step-flow growth. But the surface morphology was not smooth since the purging time of of 1s after AsH_3 flow was too small to complete the evaporation of As trimers at 750 °C. Hence, FME growth was carried out by changing the purging time from 1 to 2s. Each sample almost kept their initial shapes after growth (Fig.4).

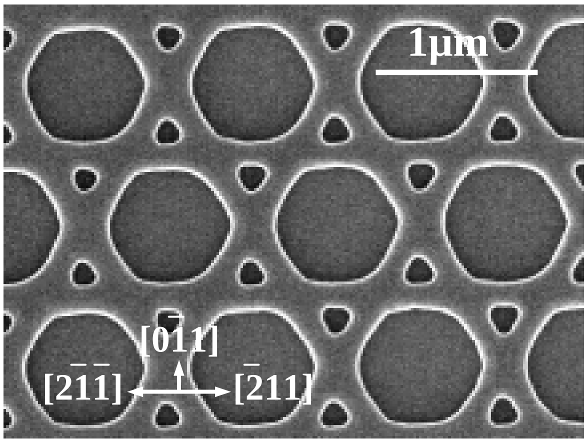

Fig.4 SEM image of 1 μm-period Kagome lattice structure growth with optimized conditions

4. Summary

GaAs Kagome lattice structure of 1μm-period was successfully grown by selective area metalorganic vapor phase epitaxy on GaAs (111)B substrates. The results obtained can be extended to the growth of Kagome lattice structure with still smaller periods for experimental observation of ferromagnetism.

References

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