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Molecular States of Coupled Zero-Dimensional Structures Imaged Using Low-Temperature Scanning Tunneling Spectroscopy

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1. Introduction

Recently, zero-dimensional (0D) structures have been considered to be key devices in future quantum information technologies. We studied local density of states (LDOS) of low-dimensional semiconductor structures using low-temperature scanning tunneling microscopy and spectroscopy (LT-STM and LT-STS) to better understand electron behavior in such structures [1-4]. In this paper, coupled InAs structures were examined to characterize molecular states in dimerized 0D resonant structures.

2. Experiments

Undoped InAs layer was grown on an n-GaAs(111)A substrate by molecular beam epitaxy (MBE). The sample was then transferred to the LT-STM stage in an ultra-high-vacuum below 10^{-10} Torr and cooled to 5 K. The surface LDOS was obtained by using dI/dV measurement with a lock-in technique, which was done simultaneously with LT-STS [3, 4]. The map of dI/dV/(I/V) values is known to correspond to the distribution of LDOS.

3. Results and Discussion

At the epitaxial InAs surface, not only single stacking fault tetrahedrons (SFTs) [1-4], but also differently formed stacking fault structures were found. One of such structures is a nanostructure with narrowing in the central region (Figs. 1(a) and 2(a)). The crystallographic geometry appears to have a coupled structure of two SFT components eventually interacted with each other and joined. It was found that there were two different types in the coupling feature. The type I structure is a single crystal without a boundary in the central region. This means that there is no barrier inside the structure and electronic states on one side of the structure can effectively interfere with those on the other side through the central narrow region. The type II structure is a pair of SFTs with a boundary of a fractional monolayer height step in the central region as shown by arrows in Fig. 2(a). One of apexes of the SFT on one side is truncated forming an interface with the SFT on the other side. The interface is a {111} stacking fault plane, which plays the role of a barrier to disturb the interference between components due to the differently polarized nature there. Since both types of nanostructures could be considered coupled zero-dimensional resonant structures, we could investigate both the nature of the coupling between components and the role of the barrier in such semiconductor nanostructures.

The dI/dV/(I/V)-V spectrum averaged in the type I structure had a broad peak around the bias voltage between 0.02 and 0.06 V with showing existence of discrete levels (Fig. 3(a)). In a single SFT with the same size, 1st and 2nd 0D levels were found around this bias range [3]. Typically, dI/dV/(I/V)-V spectrum averaged only in the central region showed a peak (arrow B) with LDOS distribution as a loop, and a valley (arrow A) with nodal LDOS distribution (Fig. 1(b)). Here, brighter region in images has higher LDOS. The interior LDOS had different distribution from those of single SFTs, and behavior of LDOS in the narrow region never happened in single SFTs [1-4]. Thus, it is suggested that the LDOS of the type I structure can be approximately described by assuming that 0D states in two components are hybridized to form bonding and antibonding states. Though further investigation is necessary for quantitative understanding, the tendency of molecular coupling between components appears in LDOS of the type I structure.

However, LDOS patterns and their energy separations in each SFT component of the type II structure exhibited similar 0D features to those of single SFTs (Fig. 2(b)). The dI/dV/(I/V)-V spectrum averaged in the central region showed a similar bias voltage dependence to that averaged inside the structure (Fig. 3(b)). In particular, the dI/dV/(I/V)-V spectrum in the central region were increased around the bias voltages where LDOS patterns similar to those of single SFT were imaged. Therefore, in the type II structure, atomic behavior is dominant in individual component. This is because the barrier at the interface screened out wavefunction penetration from a component to the neighbor one [2].

4. Conclusions

The local density of states of coupled 0D structures made of double SFTs was characterized using LT-STS. In the case of a coupled structure without a barrier between its components, dI/dV/(I/V) images revealed LDOS of bonding and antibonding states due to molecular coupling between components. However, in similar nanostructure with a barrier between components, individual component was found to show atomic behavior and exhibited its own 0D states like single SFTs. It was found that the barrier of the stacking fault plane strongly screened out the effect of

surrounding electronic states and confined electrons inside the stacking fault structures.

Acknowledgements

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References

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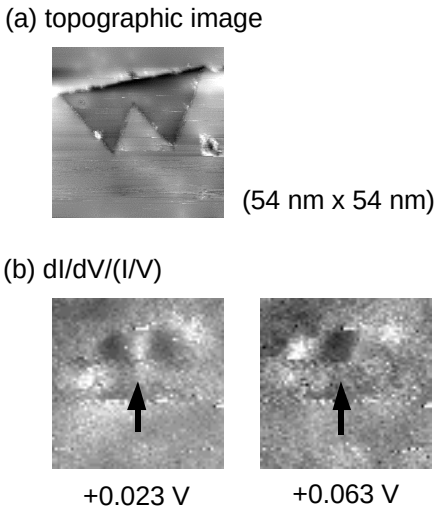

Fig. 1 (a) Topographic image of coupled zero-dimensional structure without barrier (type I). (b) Corresponding dI/dV/(I/V) images of peak B and valley A in Fig 3(a) are also shown. Each arrow indicates LDOS in the central region of the structure.

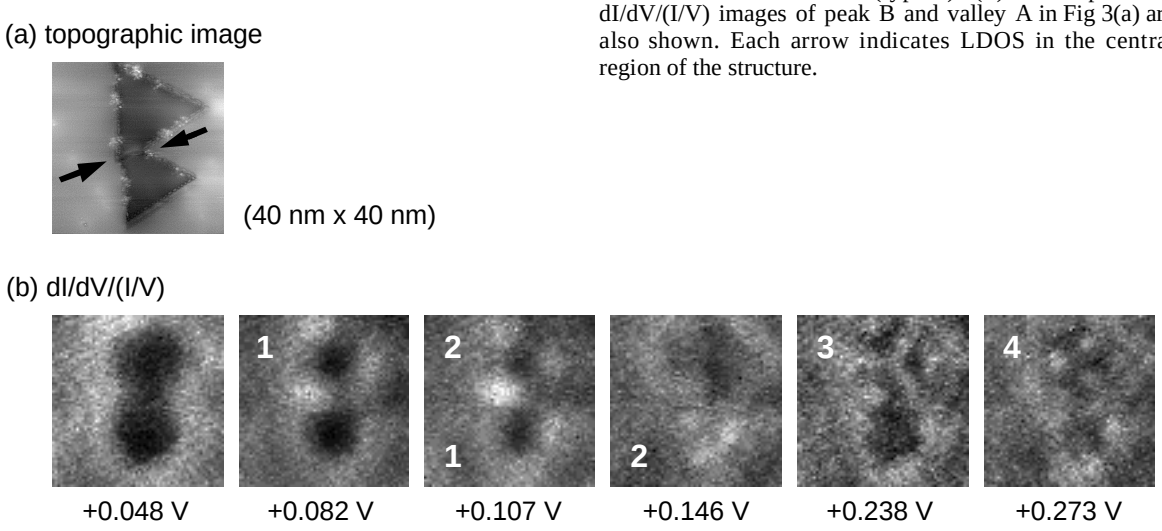

Fig. 2 (a) Topographic image of coupled zero-dimensional structure with barrier (type II). Arrows indicate barrier (interface plane) position. (b) Each corresponding dI/dV/(I/V) image shows individual 0D LDOS pattern in each component. Number *n* in each image is an index of *n*-th 0D state of upper or lower component.

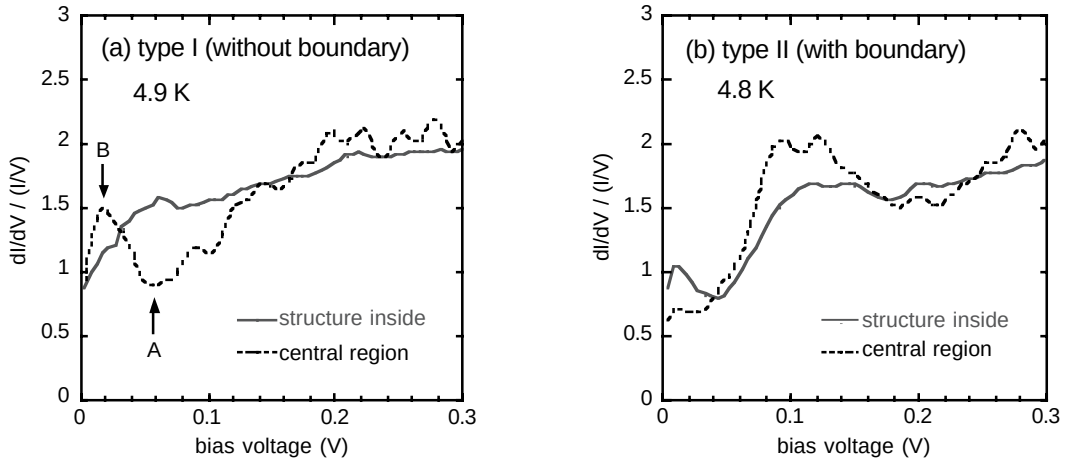

Fig. 3 The dI/dV/(I/V)-V spectra of (a) type I and (b) type II structures in Figs. 1 and 2. Solid curve indicates LDOS averaged at whole of area inside the structure. Dashed curve indicates averaged LDOS only in the central region of the structure. LDOS patterns shown in Fig. 1(b) were imaged at bias voltages of peak B and valley A.