

Spatial Distribution of Impurity States of Cr Atoms in (Zn,Cr)Te Studied by STM

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1. Introduction

In recent years, so-called “spintronics”, which utilize both of charge and spin of carriers, is extensively investigated. Diluted magnetic semiconductors (DMSs) have been energetically studied because of their possibility of application to future semiconductor-spintronic devices. Especially, (Zn,Cr)Te has been regarded as one of the promising materials with its intrinsic room-temperature ferromagnetism when Cr composition is about 20 % [1]. The ferromagnetic interaction between magnetic moments of Cr, which substitute for cation sites in ZnTe is considered to be of short-range character, differently from the case of (Ga,Mn)As, and the double-exchange or super-exchange interaction has been proposed as a possible mechanism of this interaction [2]. On the other hand, the local electronic state of Cr in ZnTe has not yet been clarified experimentally. The information of the electronic state of Cr in an atomic scale, such as the spatial distribution of electron orbitals or density of states (DOS), is considered to be essential for the understanding the magnetic interaction between Cr.

Therefore, in this study, we performed scanning tunneling microscopy / spectroscopy (STM / STS) measurement for (Zn,Cr)Te, since STM has very high spatial resolution ($< 1 \text{ \AA}$) in real space, and tunneling current (I_t) of STM is very sensitive to local DOS at a particular energy level corresponding to applied sample bias voltage (V_s).

2. Experimental methods

A multi-layered sample structure consisting of a (Zn,Cr)Te layer on a buffer non-doped ZnTe (ND-ZnTe) layer was fabricated by molecular beam epitaxy (MBE) on a p-ZnTe(001) substrate at 573 K. Figure 1 shows a schematic illustration of the sample structure. The Cr composition was about 5% and the thicknesses of the (Zn,Cr)Te and ND-ZnTe layers were about 360 nm and 10 nm, respectively. The growth of the MBE films was monitored by reflection high energy electron diffraction (RHEED). After we cleaved the sample in high vacuum ($\sim 10^{-5}$ Pa) in a load lock chamber in order to obtain a clean cross-sectional surface, it was installed in an ultra-high vacuum STM chamber ($< 10^{-8}$ Pa) without any exposure to air. All STM/STS measurements were performed at 77 K using an electrochemically sharpened polycrystalline tungsten tip ($\phi = 0.3$ mm). STM images were obtained with constant current mode, and STS curves were measured in open feedback loop conditions.

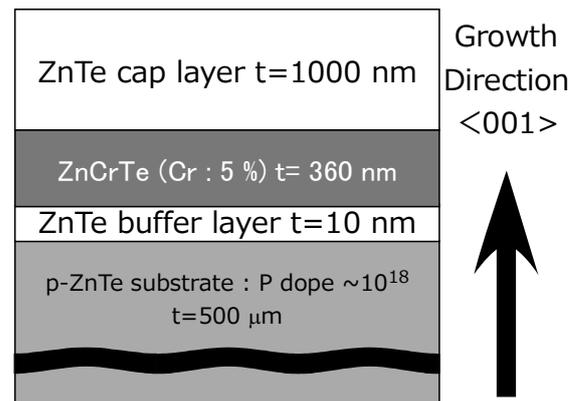


Fig.1 Schematic illustration of the sample structure for cross-sectional-STM.

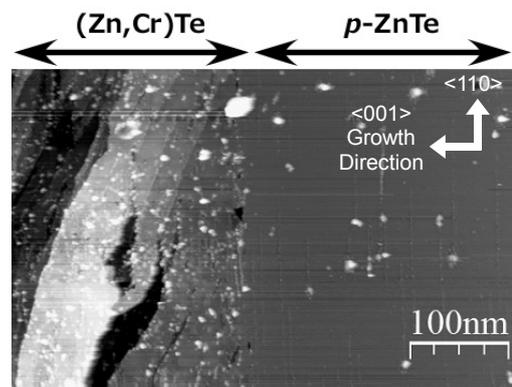


Fig.2 STM topographic image of (Zn,Cr)Te / ZnTe / p-ZnTe multilayer region ($V_s = +5.0$ V, $I_t = 20$ pA).

3. Experimental results and discussions

Figure 2 shows a typical STM image obtained on the p-ZnTe/ND-ZnTe/(Zn,Cr)Te cross-sectional surface. The interface between the substrate and MBE layers was clearly observed. While a very clean cleaved surface with small number of bright clusters was obtained in the p-ZnTe region, large number of small bright points were also observed in the (Zn,Cr)Te region, corresponding to doped Cr atoms. In order to investigate electronic states of each layer, we measured STS curves of I_t - V_s characteristic at many points on the surface. As shown in fig.3 the I_t - V_s curves averaged over the respective layers are very different from each other. Especially, in a small positive V_s region, I_t on

the (Zn,Cr)Te layer is much larger than that on the p-ZnTe layer (inset of fig.3). These results suggest that the doped Cr atoms form impurity electronic states at deep levels within the band-gap of the host ZnTe, as proposed in earlier theoretical study [2].

Then in order to investigate the spatial extent of the Cr impurity state in smaller scale, we measured STS curves around a single Cr atom, which was detected in atomic-resolution STM images. Figure 4(a) shows a high resolutional STM image obtained in the (Zn,Cr)Te region.

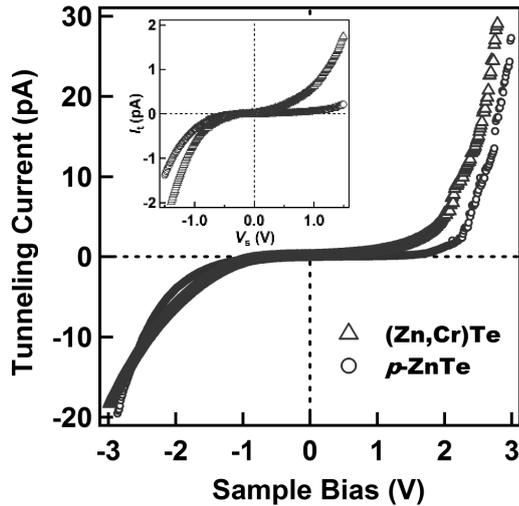


Fig.3 I_t - V_s curves measured on p-ZnTe and (Zn,Cr)Te region, respectively. Inset shows enlarged curves between $V_s = \pm 1.5$ V.

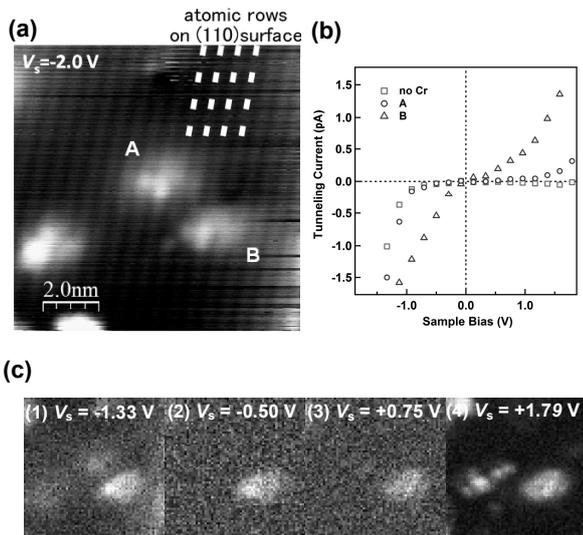


Fig.4 (a) STM topographic image of (Zn,Cr)Te region ($V_s = -2.0$ V, $I_t = 20$ pA). Dashed lines indicate atomic rows on the (110) surface

(b) I_t - V_s curves measured on three points in (Zn,Cr)Te, A and B were measured on Cr atoms as indicated by A and B in fig.4(a) and the another is measured on a point without Cr.

(c) CITS mappings measured on the same region as fig.4(a), (1) at $V_s = -1.33$ V, (2) at $V_s = -0.50$ V, (3) at $V_s = +0.75$ V, (4) at $V_s = +1.79$ V, respectively.

In addition to atomic rows along $\langle 110 \rangle$ direction as well as on a ZnTe(110) surface, we observed small protrusions, as indicated A and B, due to dopant Cr atoms located at several layers below the surface. As shown in figure 4(b), I_t - V_s curves were completely different depending on presence or absence of Cr at a measured position, as well as the difference between (Zn,Cr)Te and p-ZnTe discussed above. Moreover, we obtained current imaging tunneling spectroscopy (CITS) in this region. CITS results show that the Cr impurity states spread over in 2 ~3 nm from the position of the Cr atom. And, two Cr atoms observed similarly (A and B), have different impurity electronic states. These results indicate that the impurity states are varied by surrounding environment of the Cr atoms, such as formation of coupling states with neighboring defects or Cr atoms in the grown film.

4. Summary

In this study, we have performed scanning tunneling microscopy/spectroscopy (STM/STS) measurement for (Zn,Cr)Te, in order to clarify local electronic states of Cr atoms experimentally. The result of our STM observation in (Zn,Cr)Te confirms that the doped Cr atoms form impurity electronic states at a deep level within the band-gap of the host ZnTe. In addition, the spatially-resolved STS around the Cr atom reveals that the Cr impurity states spread over in 2 ~3 nm from the position of the Cr atom. The details of the experimented results will be presented at the conference.

References

- [1] H. Saito et al. Phys. Rev. Lett. **90**, 207202 (2003)
- [2] K. Sato et al., Semicond. Sci. Technol. **17**, 367 (2002).

Appendix

Kuroda-Lab URL: http://www.ims.tsukuba.ac.jp/~kuroda_lab