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## STM/STS を用いた希薄磁性半導体(Zn,Cr)Te 中の Cr 不純物準位の研究
## Study of Cr impurity states in diluted magnetic semiconductor (Zn,Cr)Te by STM/STS

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Cr-doped ZnTe ((Zn,Cr)Te) has been regarded as one of the promising diluted magnetic semiconductors (DMSs) for future spintronic application, because of its intrinsic room-temperature ferromagnetism when Cr composition is about 20 % [1]. As a possible mechanism of this ferromagnetic interaction between neighboring Cr atoms, the double-exchange interaction has been proposed theoretically [2]. However experimental study to verify the theoretical proposal has not been enough. In order to investigate information of such short-range interaction, we performed scanning tunneling microscopy / spectroscopy (STM / STS) measurement for (Zn,Cr)Te.

A (Zn,Cr)Te film (250 nm) was grown by molecular beam epitaxy on a p-ZnTe substrate with a buffer undoped ZnTe layer (10 nm) at 300 ℃. The Cr composition was estimated to be about 5 %. In order to obtain clean cross-sectional surface for STM observation, we cleaved the multilayer sample in high vacuum chamber (~$10^{-5}$ Pa) and installed it to UHV STM chamber without any exposure to air. All STM / STS measurements were performed at 77 K or 8 K.

As shown in Fig.1, we observed single Cr atoms as atomic-scale protrusions at a sample bias voltage ($V_s$) of -2.0 V. Chromium atoms were classified into two types by their heights as indicated by L (low) and H (high), respectively. In order to clarify the two types of structure, we calculated the spatial distribution of local density of states (LDOS) near the Fermi energy ($E_F$) by density functional theory (DFT). As shown in Fig.2, the distribution on the topmost surface is different depending on the position of Cr atoms locating in the first or second (110) atomic layer. From these results, we conclude that bright points labeled by H (L) correspond to Cr atoms in the second (first) layer. Here, in order to investigate electronic states of Cr atoms, we performed STS measurement. As shown in Fig.3, the d$I$/d$V$-$V$ curves were completely different depending on presence or absence of Cr at a measured position; in a small $V_s$ region, d$I$/d$V$ on a Cr atom was much larger than that on a position without Cr atoms. This result suggests that a doped Cr atom formed an impurity state at a deep level within the band-gap of the host ZnTe, as proposed by the earlier first principles theoretical study [2]. Moreover, the STS results also indicate that d$I$/d$V$-$V$ curves on Cr atoms with neighboring Cr atoms rose at smaller negative bias voltages than those on single Cr atoms. This suggests that the impurity states were broadened by coupling with neighboring Cr atoms. In the presentation, we will discuss more detail of the impurity states with showing results of our DFT calculation.
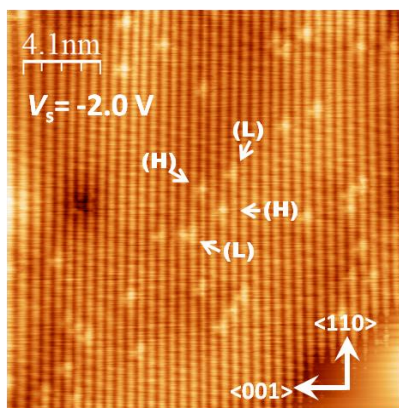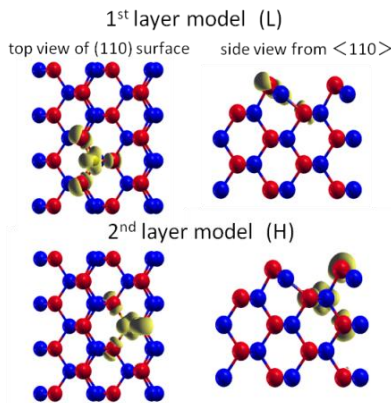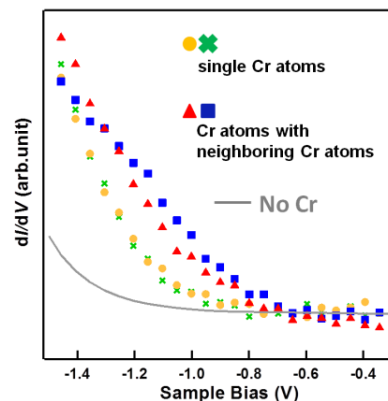
[1] H. Saito *et al*. Phys. Rev. Lett. **90**, 207202 (2003)
[2] K. Sato *et al*., Semicond. Sci. Technol. **17**, 367 (2002).

Fig.1 STM topographic image of single Cr atoms in the (Zn,Cr)Te layer.
(set point : $V$ = -2.0 V, $I$ = 20 pA).



Fig.2 spatial distribution of LDOS integrated on $E_F$ - 0.1 eV ＜ $E$ ＜ $E_F$ calculated by DFT.



Fig.3 d$I$/d$V$-$V$ curves measured on the (Zn,Cr)Te layer.
(set point : $V$ = -5.0 V, $I$ = 20 pA)