Electronic structure of Ga$_{1-x}$Cr$_x$As studied by in-situ photoemission spectroscopy

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Introduction
Since the first reports of ferromagnetism in Mn-doped III-V semiconductors synthesized the “spinelectronics” research field using molecular-beam epitaxy (MBE), diluted magnetic semiconductors (DMS) have become key materials for the functional device application combining magnetic and semiconducting properties[1]. The Mn doping into GaAs leads to carrier-induced ferromagnetism because hole carriers introduced into the Mn ions although its microscopic mechanism has been controversial until now. The Curie temperature ($T_C$) in Ga$_{1-x}$Mn$_x$As has not exceeded 150 K so far due to the solubility limit of Mn and the carrier self-compensation[2]. To overcome these problems in Ga$_{1-x}$Mn$_x$As, the investigations for the chemical trends in III-V based DMS can bring us a new information about a functional material design. First-principle band-structure calculation predicts that the Cr doping into GaAs stabilizes the ferromagnetic states because the Cr 3$d$ states are located near the Fermi level ($E_F$)[3]. The Cr doping into GaAs has a high potential to design the high-$T_C$ ferromagnetic semiconductors. We have fabricated the Ga$_{1-x}$Cr$_x$As by MBE and discussed the electronic structure by the Cr doping into GaAs using in-situ photoemission spectroscopy. We focused on the transition-metal 3$d$ states in Ga$_{1-x}$Cr$_x$As comparing with those in Ga$_{1-x}$Mn$_x$As[4].

Experimental
Ga$_{1-x}$Cr$_x$As samples were grown by low-temperature (LT) -MBE methods on GaAs (001) substrates. The 100-nm Ga$_{1-x}$Cr$_x$As layer was grown on the GaAs buffer layer at 200°C and the evaporation temperature of Cr ions was changed from 1140°C to 1240°C to fabricate the different Cr-concentration samples. The MBE system used in this study was connected to the synchrotron-radiation photoemission spectroscopy chamber at BL-1C of Photon Factory, High-Energy Accelerator Research Organization (KEK). The samples grown by MBE were transferred into the photoemission chamber without breaking the ultrahigh vacuum. In-situ photoemission spectroscopy was performed at room temperature.

Results and discussion
Figure 1 shows the valence-band spectra of Ga$_{1-x}$Cr$_x$As depending on the Cr concentration. As references, spectrum for GaAs is also shown. Valence-band spectra taken at photon energy $h\nu = 60$ eV show new states near $E_F$ derived from the Cr 3$d$ states as shown by arrow in Fig. 1. One can see that the intensity in new states depends on the Cr concentration. These states appear by the hybridization between Cr 3$d$ and As 4$p$ states. Peak positions are shifted toward lower binding energy with increasing the Cr concentration, suggesting the Fermi-level shifts due to the hole doping. The Cr substitution into Ga site will derive the hole doping by $\text{Cr}^{3+} \rightarrow \text{Cr}^{2+} + \text{hole}$ through the hybridization between Cr 3$d$ and As 4$p$ states. Spectra for higher Cr concentrations than 11% doping show a clear Fermi edge. For Ga$_{1-x}$Mn$_x$As, the Mn 3$d$ states are located around ~4 eV and $p-d$ exchange interaction through the hybridization Mn 3$d$ and As 4$p$ states is important for the ferromagnetic ordering[4]. On the other hand, the new states appearing by the Cr doping may be responsible for the double-exchange mechanism for the ferromagnetism.

References

![Figure 1: Valence-band photoemission spectra of Ga$_{1-x}$Cr$_x$As depending on the Cr concentration.](kanai@sr.t.u-tokyo.ac.jp)