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Band structure of GaMnAs near the Fermi level studied by ultrafast time-resolved light-induced reflectivity measurements

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There have been intense discussions over the position of the Fermi level (E_F) in ferromagnetic semiconductor GaMnAs [1-4]. While a number of studies have indicated that E_F exists in the impurity band (IB) in the band gap (E_g) [3-4], recent time-resolved measurements in terms of the light-induced reflectivity have indicated that E_F exists in the valence band (VB) [2]; however, the pump fluence in this study is rather high, and the accumulation of the photo-carriers induced by the pump pulse irradiation may shift the absorption edge [5]. In this case, the definition of both E_g and E_F is obscure. In our study, we have carefully performed the pump and probe reflectivity measurements with the pump pulse having very low fluence to suppress the accumulation of the photo-induced carriers.

We used 20-nm-thick $Ga_{1-x}Mn_xAs$ films with the Mn concentration x of 1%, 3%, and 6% grown on semi-insulating (S.I.) GaAs (001) substrates. The Curie temperatures of these samples are 13 K, 38 K, and 120 K, respectively. Time-resolved reflectivity measurements were performed by using degenerate pump-probe technique. A pulsed laser with the time duration of 3 ps and a repetition rate of 80 MHz was used as a light source. The photon energies of the pump and probe pulses were set in the vicinity of the resonance of the band-to-band transition in the GaMnAs samples. At the delay time t after the irradiation of the pump pulse with the fluence of 0.16 μJ/cm^2, the low-power probe pulse with 1 nJ/cm^2 detects the reflectivity change $\Delta R/R$. By assuming that the pump-pulse light is absorbed only in the GaMnAs layer, the density of the photo-excited carriers is estimated to be below 3×10^{17} cm^{-3}, which is two orders of magnitude smaller than that in the previous study [2]. The photon energy resolution of our set-up is estimated to be ~0.5 meV, which is much higher than that in the previous works [2,6].

In this study, we determine the position of the E_F by analyzing the time-resolved reflectivity spectrum. Figure 1(a) shows $\Delta R/R$ measured at 5 K for the S.I. GaAs substrate and for the $Ga_{1-x}Mn_xAs$ films at t=166 ps. Here, E_g and E_F are assigned as shown in Fig. 1(a) by the Kramers-Kronig analysis of the reflectivity spectrum. Generally, the band filling (BF) induces a positive $\Delta R/R$ peak above E_g (or E_F), while the band-gap renormalization (BGR) induces a positive $\Delta R/R$ peak below E_g (or E_F) as shown in Fig. 1(b) and Fig. 1(c). The positive $\Delta R/R$ peaks in Fig. 1(a) indicated by the red triangles, black squares, and black triangles are attributed to the electron transition from shifted E_F due to BF to the conduction band (CB), the electron transition corresponding to shifted E_g (from VB to CB) due to BGR, and the electron transition corresponding to shifted E_g due to BF, respectively. We found that E_g-E_F increases with increasing x from 1%. This behavior is consistent with the previous study indicating that E_F moves away from VB with increasing x [4]. The obtained values of E_g-E_F in our study are ~40 meV smaller than those obtained in the previous report [3]. This may imply that there is still a small amount of influence of photo-carriers (~10^{17} cm^{-3}), which have a long life time and slightly shift the absorption edge.

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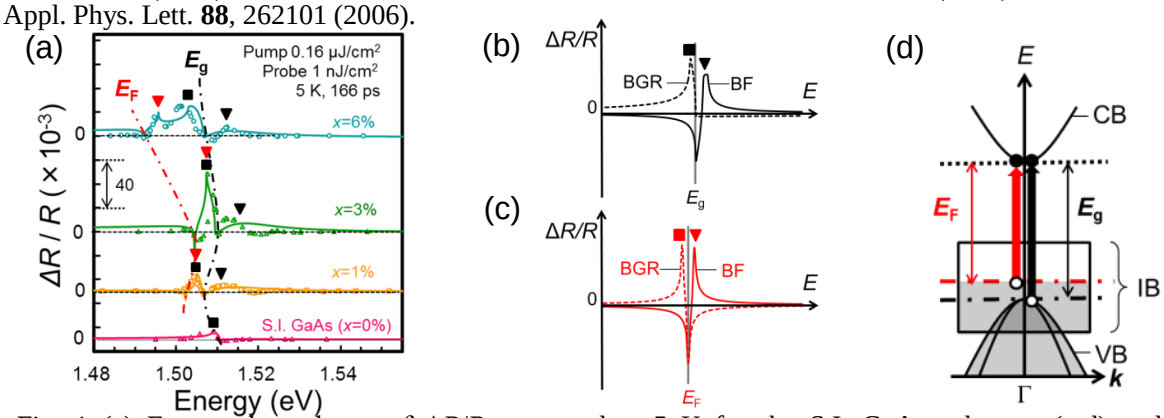

Fig. 1 (a) Energy dependence of $\Delta R/R$ measured at 5 K for the S.I. GaAs substrate (red) and the $Ga_{1-x}Mn_xAs$ films with x=1% (orange), 3% (green), and 6% (blue) at t=166 ps. The solid curves are fitting curves calculated by the Kramers-Kronig analysis. (b) Schematic $\Delta R/R$ components due to BF (black solid curve) and BGR (black dotted curve) near E_g [5], and (c) due to BF (red solid curve) and BGR (red dotted curve) near E_F. (d) Photo-induced electron transitions from E_F to the CB (red arrow) and from VB to CB (black arrow) in GaMnAs.