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

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There have been intense discussions over the Fermi level (E_F) position in GaMnAs [1-4]. So far a number of studies have indicated that E_F exists in the impurity band (IB) in the band gap (E_g) [3-4], while recent time-resolved light-induced reflectivity measurements have shown conflicting results indicating that E_F exists in the valence band (VB) [2]. This conflict may be due to a high fluence pump, giving a quite dense photo-excited carrier density 4×10^{19} cm^{-3} and significant change in the band structure [5], and thus the definition of both E_g and E_F are obscure. In this study, we carefully carry out time-resolved reflectivity measurements with low fluence pump to suppress the accumulation of photo-carriers.

We grew 100-nm-thick $Ga_{1-x}Mn_xAs$ films with x=1%, 3%, and 6% after growing a 20-nm-thick GaAs buffer layer on semi-insulating (S.I.) GaAs (001) substrates by low-temperature molecular beam epitaxy. The $Ga_{0.94}Mn_{0.06}As$ film was annealed at 240ºC for 89 h. The Curie temperature of the $Ga_{0.99}Mn_{0.01}As$, $Ga_{0.97}Mn_{0.03}As$, and $Ga_{0.94}Mn_{0.06}As$ films is 13 K, 38 K, and 120 K, respectively. Time-resolved reflectivity measurements were performed by using pump-probe procedure and a pulsed light source with time-duration of 3 ps and a reputation rate of 80 MHz. At 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 and the same photon energy as that of the pump light was irradiated to the sample, probing the reflectivity change $\Delta R/R$. Photo-excited carrier density is estimated to be below 3×10^{17} cm^{-3} by assuming that the pump-pulse light is absorbed only in the GaMnAs layer. This is two orders magnitude smaller than the carrier density for the previous study [2]. We used the pico-second pulses to achieve the high energy resolution of ~1 meV.

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. Generally, as shown in Fig. 1(b), positive$\Delta R/R$ peaks are observed above E_g due to band filling (BF) and near E_g due to band-gap renormalization (BGR). Figure 1(c) shows possible photo-induced electron transitions in GaMnAs. In Fig. 1(a), a clear peak is observed at ~1.51 eV (pointed by the green arrow) for all the samples. This can be attributed to BGR and thus assigned to E_g. In the data for the GaMnAs films, we see clear structures in the region having lower energy than E_g, which means that electrons (and thus E_F) exist in the band gap (Fig. 1(c)). The peaks pointed by red arrows in Fig. 1(a) are attributed to BGR due to photo-carriers excited from E_F to CB. Also, the positive peak observed between the red and green arrows when x=3% and 6% is attributed to BF induced by electrons excited from IB to CB. The BGR peaks pointed by the red arrow shifts to the lower energy with increasing x from 1%, which is consistent with the previous resonant tunneling experiments indicating that E_F moves away from VB with increasing x from 1% [4]. The energy difference from E_F to the top of VB in $Ga_{0.94}Mn_{0.06}As$ in our study is ~40 meV smaller than that in the previous report [3]. This may imply that there is still a small amount of influence of photo-carriers, which have a long life time and slightly shift the absorption edge.

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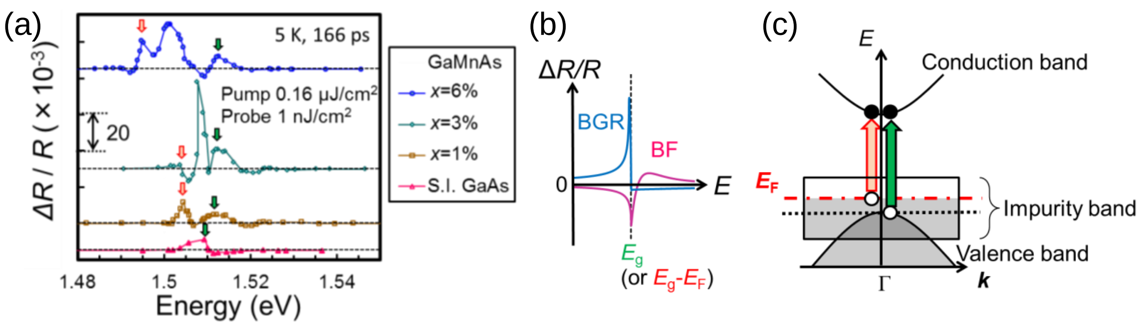

Fig. 1 (a) Energy dependence of $\Delta R/R$ measured at 5 K for the S.I. GaAs substrate (red) and the $Ga_{1-x}Mn_xAs$ films with x=1% (brown), 3% (green), and 6% (blue) at t=166 ps. The red and green arrows are the positive ΔR peaks caused by BGR induced by the electrons excited from E_F to CB and from VB to CB, respectively. (b) Schematic $\Delta R/R$ components due to BF (red curve) and BGR (blue curve) [5]. If the peak of the positive $\Delta R/R$ component due to BGR is larger than the peak of the negative $\Delta R/R$ component due to BF, the positive $\Delta R/R$ peak near E_g due to BGR can be observed. (c) Photo-induced electron transitions from E_F to the CB (red arrow) and from VB to CB (green arrow) in GaMnAs.