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Optical characterization of $Ga_{0.965}Mn_{0.03}Cr_{0.005}As$ thin film grown by molecular beam epitaxy

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Abstract

In this study, optical properties of Chrome (Cr) and Manganese (Mn) containing GaMnCrAs epilayer are investigated using temperature dependent photoconductivity (PC) technique. Alloy composition is determined with secondary ion mass spectroscopy as 3% Mn and 0.5% Cr in GaMnCrAs. Scanning electron microscopy (SEM) image shows that the interface between GaAs buffer layer and GaMnCrAs epilayer is not abrupt and thread-like dislocations in GaAs are present. We observed the highest PC signal at the lowest temperature (T= 30 K) which can be explained in terms of non-activated defects at such low temperatures. At the intermediate temperatures, PC signals were suppressed due to the activation of the defects causing to trap of the photo-generated carriers. Such behaviour is originated from the semi-insulating character of the samples. Since photo-generated and thermally activated carriers are trapped by defects in the GaMnCrAs epilayer at high temperatures, the clear PC signal can be only observed both below and above fundamental bandgap energy of GaAs, while no optical transition between the band edges.

Keywords: Magnetic semiconductor, GaMnCrAs, Photoconductivity, Semi-insulating, Defect, Optical transition

Moleküler demet epitaksi ile büyütülen $Ga_{0.965}Mn_{0.03}Cr_{0.005}As$ ince filmin optik karakterizasyonu

Özet

Bu çalışma kapsamında, Krom (Cr) ve Mangan (Mn) içeren GaMnCrAs epitabaka yapının optik özelliği sıcaklığa bağlı fotoiletkenlik (Fİ) tekniği ile araştırılmıştır. GaMnCrAs'in alaşım kompozisyonu ikincil iyon kütle spektroskopisi ile %3 Mn ve %0.5 Cr olarak belirlenmiştir. Taramalı Elektron Mikroskobu (SEM) görüntüsünden GaAs tampon tabakası ve GaMnCrAs epitabakası arayüzeyinin keskin olmadığı ve dislokasyonların olduğu gözlenmiştir. Fİ ölçümleri sonucunda, en şiddetli Fİ sinyali 30 K gibi düşük sıcaklıklarda elde edilmiştir. Bu durum düşük sıcaklıklarda aktif olmayan kusurlardan kaynaklanmaktadır. Orta sıcaklıklarda, aktif hale gelen kusurların foto-uyarılmış taşıyıcıları tuzaklamasından kaynaklı Fİ sinyali baskılanmıştır. Bu durum örneklerin yarı-yalıtkan karakterisitiğinden kaynaklanmaktadır. Tüm foto-uyarılmış ve termal olarak uyarılarak aktive olmuş taşıyıcılar yapı içerisinde bulunan doğal kusurlar tarafından tuzaklanmaktadır. Yüksek sıcaklıklarda Fİ sinyali GaAs'in band aralığı enerjisinin altında ve üstünde net bir şekilde elde edilmişken band kenarlarında herhangi bir optik geçiş gözlemlenmemiştir.

Anahtar Kelimeler: Manyetik yarıiletken, GaMnCrAs, Fotoiletkenlik, Yarı-yalıtkan, Tuzak, Optik geçiş.

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1. Introduction

Dilute magnetic semiconductors is considered as potential candidate for spintronic applications [1], similarly Bi-containing alloys [2–4]. Doping or alloying of III-V semiconductor with a transition metal, such as Mn and/or Cr, gives opportunity to have magnetic characteristics and tailoring of magnetic properties [5]. In corporation of the Mn atom into GaAs at low temperatures generates localized level above valence band (VB) edge as ~0.110 eV due to the occupation of Mn as interstitial position [6]. Increasing amount of the Mn atoms causes localized Mn level to overlap with VB edge and then goes into the VB [7,8]. Hence, the effect of the Mn incorporation on bandgap induces a shrinkage of the alloy's bandgap [9]. As a counterpart of GaMnAs for ferromagnetic application, GaCrAs alloys have also similar electronic bandstructure, but defect level is close to conduction band (CB) edge [10]. Moreover, Mn and Cr atoms generate different energy states inside the CB. Ibanez *et al.* reported that the free hole density increases with Cr concentration inducing an increment of the localization level and carrier transport properties for GaMnCrAs alloys.

In this study, the optical properties of the GaMnCrAs alloy were investigated at temperature range between 30 and 300 K. The structural properties and optical transition energies were determined by scanning electron microscopy (SEM), and temperature dependent photoconductivity (PC) measurements, respectively.

2. Materials and methods

$Ga_{0.965}Mn_{0.03}Cr_{0.005}As$ film was grown on (001) SI-GaAs substrates by molecular beam epitaxy (MBE). A 20 nm GaAs buffer layer and 100 nm $Ga_{0.97-x}Mn_{0.03}Cr_xAs$ epitaxial layer were grown at temperatures 580 and 220 ±10 °C, respectively. The low temperature growth was employed due to effectively incorporate Mn and Cr atoms in the structure. A secondary ion mass spectroscopy was employed to determine the Mn and Cr concentrations of the samples. The sample structure is given in Table 1.

Table 1. The investigated sample structure with nominal thickness

$Ga_{0.965}Mn_{0.03}Cr_{0.005}As$ Epitaxial film (100nm)
GaAs Buffer (20nm)
SI-GaAs Substrate

Temperature dependent photoconductivity (PC) measurements were carried out at a steady state mode between the temperatures 30 and 300 K. The samples were excited with monochromatic light obtained with a 0.5 m Acton monochromator from 100 W halogen lamp. To obviate second order effect on the PC signal, two second order filters with cut-on wavelength at 560 nm and 715 nm) were utilized in the experiments. The spectrum of the excitation source was detected with a pyro detector to normalise the PC spectrum. Further detail for experimental technique can be found in elsewhere [11].

3. Results and discussion

The cross-sectional SEM image of the sample which was taken using a scanning electron microscope (SEM; FEI Quanta-650) is given in Figure 1. The top layer of $Ga_{0.965}Mn_{0.03}Cr_{0.005}As$ is approximately 100nm and the interface between this layer and GaAs buffer layer is not abrupt. It is also clear that thread-like dislocations are present. Since the growth temperature was much lower compared to the optimal growth temperature of GaAs, the observed non-abrupt interface and thread-like dislocation formation mainly in GaAs substrate might be originated from low growth temperature conditions. Using the cross-sectional SEM, the epilayer thickness is determined as 90±2 nm and observed thread-like dislocation formation in GaAs buffer is also present in the $Ga_{0.965}Mn_{0.03}Cr_{0.005}As$ epilayer with an ignorable density.

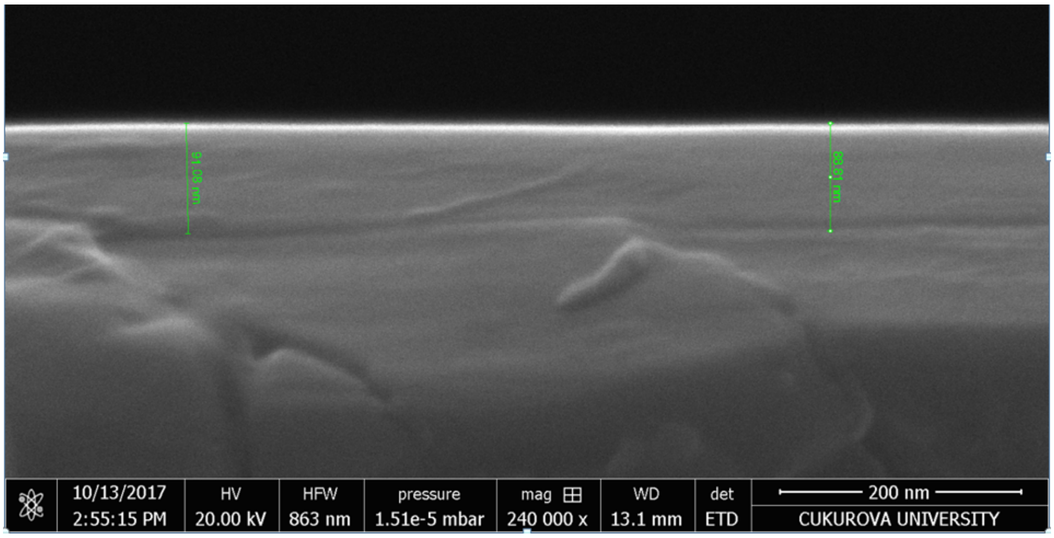

Figure 1. Cross-sectional SEM image of the sample.

In order to determine the optical properties of the $Ga_{0.965}Mn_{0.03}Cr_{0.005}As$ layer, the temperature dependent PC measurements were carried out. Figure 2 showed the PC spectrum of the sample at temperatures of 30 and 300 K. Sharp GaAs-related peaks, which were at ~1.5 (30 K) and 1.4 eV (300 K) were observed, exhibiting excellent match with the energy levels of GaAs bandgap energy [12]. Two distinct PC signals, whose energies are higher and lower than the fundamental GaAs bandgap energy, were detected together with GaAs-related PC signals. The latter PC signal started from ~1.15 eV and suddenly increased at 1.2 eV then show small rise at ~1.35 eV, just before the GaAs-related sharp peak at 30 K However, PC signal at 300 K is quite broaden feature between ~0.9 eV and 1.3 eV then reaches its maximum value at ~1.35 eV. The former PC signal starts increasing at 1.90 eV at 30 K. On the other hand, no PC signal at around 1.9 eV is observed at 300 K.

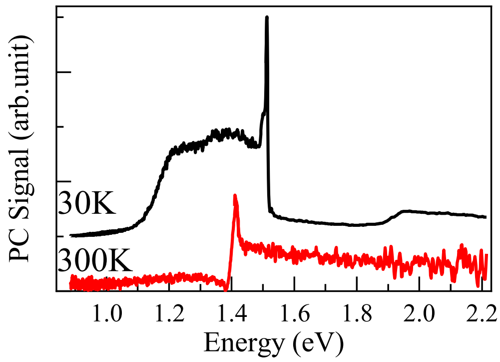

Figure 2. Normalized PC spectra of the sample at 30 and 300 K. Black and red colours depict the results for 30 and 300 K, respectively.

Alberi *et al.* explained the bandgap shrinkage of GaMnAs with two different mechanisms. The first mechanism so-called band-anticrossing is based on interaction of localised Mn level the VB of the host material, leading to splitting of the VB into the two bands. [6]. And the second mechanism is the formation of impurity band with increasing Mn content. Pela *et al.* showed by exploiting first-principle calculation of GaMnAs within GGA-1/2 method that the bandgap of the GaMnAs are shrunk due to both impurity level and interaction of the localised Mn level with VB of the host GaAs [9]. Moreover, Ibanez *et al.* showed that Cr atom generates a deep defect level in GaAs. [13]. In our GaMnCrAs sample, the PC signal below GaAs bandgap might be originated from the optical transition from the impurity band of Mn to CB.

Figure 3 shows the temperature dependent PC spectra of the sample. The PC spectra were divided into two regions corresponding below and above the GaAs bandgap energies, respectively. For below GaAs transition in Figure 3a), PC signal decreases with increasing of temperature up to 50 K, while the signal goes to zero expanding the GaAs transition energy at temperature range between 77 and 150 K due to lower signal/noise ratio as a result of trapping of the photo-generated carriers. The PC signal becomes almost zero between 1.15 eV and fundamental bandgap of GaAs at the temperature of 150 K. When temperature is increased such as above 150 K, PC signal is detected in the same region (1.15 eV and fundamental bandgap of GaAs) then we detected the PC signal at 300 K.

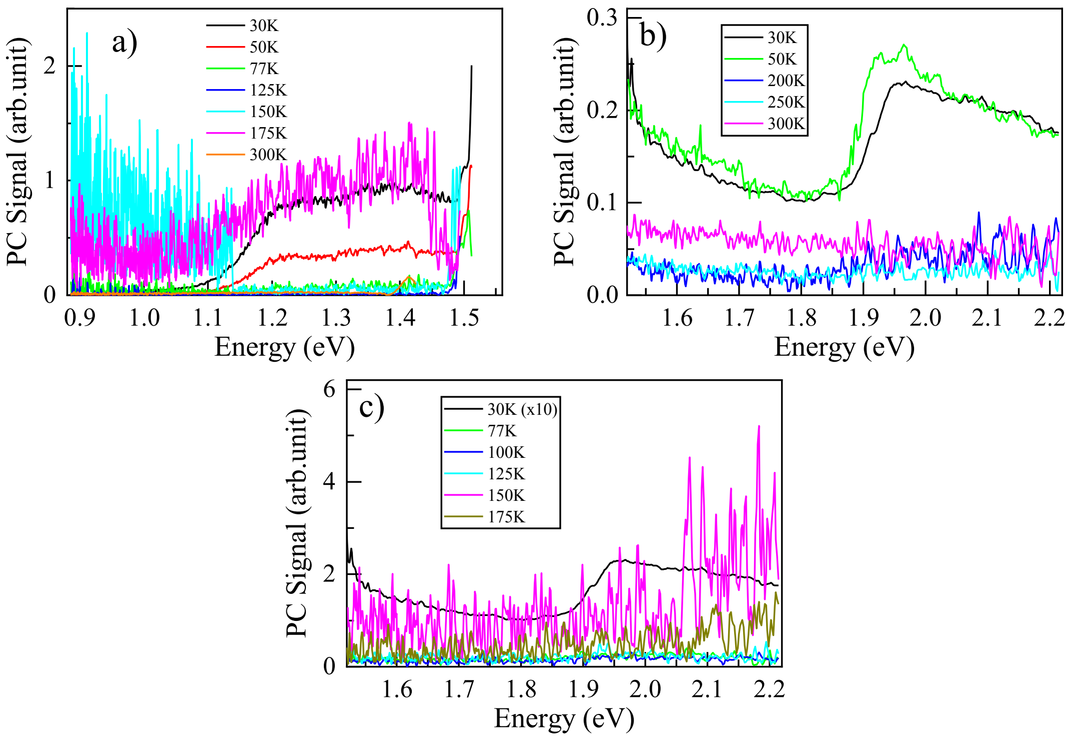

Figure 3. Temperature dependent normalized PC spectra of the sample. a) low energy region spectra taken with low pass bandedge filter (cut-on 715 nm). b) high energy region spectra taken with high pass bandedge filter (cut-on 560 nm). c) high energy region spectra taken with high pass bandedge filter (cut-on 560 nm). For comparison, 30 K result in Figure c) is multiplied by 10.

It was shown that Mn and Cr atoms generate shallow and/or deep defects in their host semiconductor [14,15]. Their defect energy levels are strongly depended upon the charge-state of the impurities and the alloy composition. Look *et al.* found that depending on lattice temperature, the ionisation status of Cr changes from Cr^{+} and Cr^{++}, resulting in different energy levels with respect to VB. Therefore, it can be concluded that below bandgap PC signals at both low and high temperatures can be related transitions from Mn and/or Cr defect levels to the CB. Figure 3 c) pointed out that at intermediate temperature range, the density of the defect levels is close to each other to quench PC signal exhibiting the semi-insulating behaviour. Moreover, the PC signal detected between 1.85-1.95 eV at 30 and 50 K in Figure 3 b) cannot be explained in terms of valence band anti-crossing model [6], since the bandgap increment is almost 10 meV per %Mn. Also, this energy range is much higher than bandgaps of GaAs and GaMnCrAs. It can be concluded that the origin of the PC signal above bandgap energies might be associated with the different ionized states of the Mn and/or Cr atom in the alloy.

4. Conclusions

The structural and optical properties of the GaMnCrAs alloy were studied. SEM images showed that the interface between GaAs and GaMnCrAs is not abrupt due to the low growth temperature of the sample. Direct optical transition was not observed between the band edges. However, PC signals were detected which might be originated from defect/impurity level at low and high temperature ranges. We considered that Mn and Cr related defect levels compensate each other between 1 eV and 1.45 eV at the intermediate temperature. Hence, this kind of materials has a great potential to comply temperature-selective semi-insulating property for optoelectronic and ferromagnetic applications. Thus, the sample shows semi-insulating behaviour due to approaching of PC signal or signal/noise ratio to zero. After increment of the temperature, quenching is eliminated by thermal energy and hence we observed PC signal again.

Ethical Statement: Scientific rules, ethics and citation rules were followed during the writing process of the study titled "Optical characterization of $Ga_{0.965}Mn_{0.03}Cr_{0.005}As$ thin film grown by molecular beam epitaxy"; No falsification has been made on the collected data and this study has not been sent to any other academic journal for evaluation.

References

[1] Wolos, A., Kaminska, M. (2008). Magnetic Impurities in Wide Band-gap III-V Semiconductors, Semicond. Semimetals, 82, 325–369. doi:10.1016/S0080-8784(08)00008-2.

[2] Donmez, O., Erol, A., Çetinkaya, Ç., Çokduygulular, E., Aydın, M.,Yıldırım, S et al. (2021). A quantitative analysis of electronic transport in n- and p-type modulation-doped GaAsBi/AlGaAs quantum well structures, Semicond. Sci. Technol, 36, 115017. doi:10.1088/1361-6641/ac2af0.

[3] Gunes, M., Ukelge, M.O., Donmez, O., Erol, A., Gumus, C., Alghamdi, H. et al. (2018). Optical properties of $GaAs_{1-x}Bi_x$/GaAs quantum well structures grown by molecular beam epitaxy on (100) and (311)B GaAs substrates, Semicond. Sci. Technol. 33 (2018) 124015. doi:10.1088/1361-6641/aaea2e.

[4] Sarcan, F., Donmez, O., Kara, K., Erol, A., Akalın, M., Arıkan, M.C. et al. (2014). Bismuth-induced effects on optical, lattice vibrational, and structural properties of bulk GaAsBi alloys, Nanoscale Res. Lett. 9, 119. doi:10.1186/1556-276X-9-119.

[5] Dietl, T. (2010). A ten-year perspective on dilute magnetic semiconductors and oxides, Nat. Mater. 9, 965–974. doi:10.1038/nmat2898.

[6] Alberi, K., Yu, K.M., Stone, P.R., Dubon, O.D., Walukiewicz W., Wojtowicz, T. et al. (2008). Formation of Mn-derived impurity band in III-Mn-V alloys by valence band anticrossing, Phys. Rev.

B - Condens. Matter Mater. Phys. 78, 075201. doi:10.1103/PhysRevB.78.075201.

[7] Bergqvist, L., Korzhavyi, P.A., Sanyal, B., Mirbt, S., Abrikosov, I.A., Nordström, L. et al. (2003). Magnetic and electronic structure of $(Ga_{1-x}Mn_x)As$, Phys. Rev. B - Condens. Matter Mater. Phys. 67,205201. doi:10.1103/PhysRevB.67.205201.

[8] Gluba, L., Yastrubchak, O., Sęk, G., Rudno-Rudziński, W., Sadowski, J., Kulik, M. et al. (2014). On the nature of the Mn-related states in the band structure of (Ga,Mn)As alloys via probing the E_1 and $E_1 + \Delta_1$ optical transitions, Appl. Phys. Lett. 105, 032408. doi:10.1063/1.4891329.

[9] Pelá, R.R., Marques, M., Ferreira, L.G., Furthmüller, J., Teles, L.K., (2012). GaMnAs: Position of Mn-d levels and majority spin band gap predicted from GGA-1/2 calculations, Appl. Phys. Lett. 100, 202408. doi:10.1063/1.4718602.

[10]Chioncel, L., Leonov, I., Allmaier, H., Beiuşeanu, F., E. Arrigoni, T. Jurcuţ, et al. (2011). Electronic correlations in short-period (CrAs)n/(GaAs) n ferromagnetic heterostructures, Phys. Rev. B 83, 035307. doi:10.1103/PhysRevB.83.035307.

[11]Erol, A., Arıkan, M.Ç. (2012). Photoconductivity and Transient Spectroscopy, Semicond. Res. Exp. Tech., Springer. doi:10.1007/978-3-642-23351-7_12.

[12]Adachi, S., (1985). GaAs, AlAs, and $Al_x Ga_{1-x} As$: Material parameters for use in research and device applications, J. Appl. Phys. 58, R1–R29. doi:10.1063/1.336070.

[13]Ibáñez, J., Edmonds, K. W., Henini, M., Eaves, L., Pastor, D., Cuscó, R. et al. (2005). Electrical characterisation of (Ga,Mn,Cr)As thin films grown by molecular beam epitaxy, J. Cryst. Growth. 278, 695–698. doi:10.1016/j.jcrysgro.2004.12.093.

[14]Feichtinger, H., Deep Centers in Semiconductors, Handb. Semicond. Technol., Wiley. doi:10.1002/9783527621842.ch4.

[15]Look, D.C., Chaudhuri, S., Eaves, L. (1982). Positive Identification of the Cr(+4)-Cr(+3) Thermal Transition in GaAs, Phys. Rev. Lett. 49, 728–1731. doi:10.1103/PhysRevLett.49.1728.