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Raman scattering study of LO phonon–plasmon coupled modes in *p*-type InGaAs

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ABSTRACT

We present a Raman scattering study of LO phonon-coupled modes in Be-doped, *p*-type $In_{0.53}Ga_{0.47}As$ with hole densities ranging from 2.2×10^{17} to 2.4×10^{19} cm^{-3}. Two separate phonon-like coupled modes are observed in the optical-phonon spectral region, corresponding to InAs-like and GaAs-like overdamped modes. With increasing free-hole density, these modes exhibit a redshift and their frequencies approach the respective TO frequencies. Unlike the case of *n*-type material, no high-frequency L^+ coupled mode could be detected. The Raman spectra are analyzed using a dielectric model based on the Lindhard–Mermin susceptibility that takes into account HH and LH intraband transitions as well as HH–LH interband transitions. The model yields good quality fits to the experimental spectra. It is shown that the inter-valence-band processes introduces an additional damping channel that causes the L^+ mode to be damped out. The comparison between the Raman spectra and the theoretical line-shape calculations suggests the presence of a residual strain and a reduced sublattice interaction in the most heavily doped samples.

1. Introduction

The coupling of LO phonons with single-particle and collective electronic excitations has been extensively studied in III–V semiconductors [1]. The interaction between LO phonon and plasmon modes via their respective macroscopic electric fields yields LO phonon–plasmon coupled modes (LOPCMs) which display a definite frequency and line-shape dependence on the free carrier density. In *n*-type binary semiconductors, usually two long-wavelength LOPCM branches are observed in Raman scattering experiments: the high-energy L^+ branch and the low-energy L^- branch. At high carrier densities, the L^- modes are phonon like and approach the TO frequency whereas the L^+ modes are plasmon like and exhibit large frequency shifts with electron density (shifts up to 700 cm^{-1} were reported in InP over the mid-10^{17}–10^{19} cm^{-3} range [2]). This latter feature makes Raman scattering by LOPCM modes a powerful tool for a contactless determination of free charge density in doped semiconductors via LOPCM line-shape analysis using suitable models [2–4]. This is particularly relevant for the characterization of nanostructures, where the realization of electrical contacts is difficult. The emerging field of nanostructure research has witnessed an increasing interest in the application of Raman scattering techniques to the evaluation of charge density in nanowires [5–7]. It is therefore important to have a good knowledge of phonon–plasmon coupling in semiconductors of technological relevance. These usually include semiconductor alloys, as alloying is commonly used to tailor the material properties for specific applications.

Whereas LOPCMs have been thoroughly investigated in binary semiconductors, reports on LOPCM in ternary semiconductors are far more scarce in the literature. Yuasa et al. [8] studied LOPCMs in *n*-type AlGaAs and observed three coupled mode branches: L^-, L^0 and L^+ arising from plasmon coupling to the GaAs-like and AlAs-like LO phonon modes, in good agreement with a Drude dielectric function model. We investigated the phonon–plasmon coupling in *n*-InGaAs in an earlier work [9], and we found a qualitatively different LOPCM behavior that could be ascribed to the strong Landau damping of the lower energy branches because of the low electron effective mass in the InGaAs alloy. The Landau damping effects could be well accounted for by using the Lindhard–Mermin model for the dielectric function.

Even more scarce are the studies on *p*-type semiconductors. Yuasa and Ishii [10] reported the observation in heavily Be-doped, *p*-type AlGaAs of three modes in addition to the two LO phonon branches. The additional modes were identified as the L^-, L^0 and

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L^+ branches of LOPCMs by analogy with those usually observed in *n*-type material. They also reported the observation of LOPCM peaks in Be-doped, *p*-type GaAs which they assigned to long-wavelength LOPCMs. This is in contrast with a previous work by Olego and Cardona [11] on Zn-doped GaAs where the LOPCM peak was attributed to large-wavevector L^- modes arising from wave-vector nonconservation. However, the analogy with LOPCM in *n*-type material was disputed in later studies performed on a wider range of hole concentrations [12,13]. These works have shown the existence in *p*-GaAs of a single long-wavelength LOPCM that evolves from the LO- to the TO-phonon frequency as the carrier density increases. The singular behavior of such LOPCM is a consequence of the overdamped nature of the hole plasma.

The InGaAs alloy is widely used in photodiodes and photodetectors for glass-fiber communications working at the 1.3–1.55 μm spectral region of minimal absorption of glass fibers, and has recently attracted interest as a material for novel ultrafast nanodipole photodetectors [14] and thermophotovoltaic cells [15]. From the standpoint of phonon coupling with the electron plasma, InGaAs is interesting because of its low electron effective mass, which confers the plasmon-like LOPCMs an enhanced sensitivity to free charge density. In addition, because of the relatively low phonon frequencies of this alloy, Landau damping strongly affects the phonon-like LOPCMs and, as shown in our earlier work [9], this qualitatively changes the LOPCM behavior relative to that typical of two-mode alloys.

To our knowledge, no clear evidence of LO phonon coupling with the hole plasma has been reported in *p*-InGaAs so far. An early study on C-doped InGaAs attributed an additional peak near the GaAs-like TO mode to a LOPCM [16], although the assignment was rather inconclusive as the frequency of the peak was insensitive to the hole concentration. In this paper we present a Raman scattering study carried out on a set of Be-doped $In_{0.53}Ga_{0.47}As$ layers lattice matched to InP, with hole densities in the range from 2.2×10^{17} to 2.4×10^{19} cm^{-3}. The results are analyzed by comparing the spectra with theoretical line shapes obtained from calculations based on the Lindhard–Mermin dielectric model. Fairly good fits to the experimental data are obtained. The contributions of the heavy-hole (HH) and light-hole (LH) intraband transitions as well as of the interband heavy- to light-hole transitions are evaluated and discussed. Phonon-like LOPCMs with a carrier-density behavior similar to that displayed by the low- and intermediate-frequency coupled modes (LFCM,IFCM) of *n*-$In_{0.53}Ga_{0.47}As$ are observed in *p*-$In_{0.53}Ga_{0.47}As$. Unlike in the case of *n*-type material, the physical origin of the phonon-like behavior is not entirely attributable to the Landau damping of the free-charge plasma that takes place at the low frequencies of the lattice phonons. Instead, the phonon-like behavior of the LOPCM modes in *p*-$In_{0.53}Ga_{0.47}As$ stems from the intrinsic overdamped nature of the two-component hole plasma that results from the interplay between the low mobility of the HH plasma, the Landau damping of the LH plasma, and the additional damping channel introduced by the inter-valence-band transitions.

2. Experiment

Four Be-doped, 500-nm thick $In_{0.53}Ga_{0.47}As$ layers, labeled *A* to *D*, were grown by molecular beam epitaxy (MBE) on semi-insulating (100)-oriented InP substrates. The temperature of the Be cell was held at 850, 900, 935, and 960 °C for samples *A* to *D*, respectively. The hole concentrations of the samples were determined by Hall measurements and were found to be 2.2×10^{17} cm^{-3} (*A*), 2.7×10^{18} cm^{-3} (*B*), 1.2×10^{19} cm^{-3} (*C*), and 2.4×10^{19} cm^{-3} (*D*). The Raman measurements were performed at 80 K on a (100) face in $x(yz)\bar{x}$ configuration. The Raman spectra were excited with the 514.5-nm line of an Ar^+ laser, with a power on the sample of ≈ 50 mW. The backscattered light was analyzed using a Jobin–Yvon T64000 spectrometer equipped with a charge coupled device detector (CCD) cooled with liquid nitrogen. The spectral resolution was better than 2.5 cm^{-1}.

3. Raman spectra

Fig. 1 shows the Raman spectra obtained from samples *A* to *D* at 80 K in the $x(yz)\bar{x}$ scattering geometry. Deformation-potential and electro-optic scattering mechanisms are allowed in this configuration, for which only the LO modes are symmetry-allowed. The spectrum of the sample with the lowest doping (*A*) resembles closely that of unintentionally doped ($N_e \sim 10^{15}$ cm^{-3}) $In_{0.53}Ga_{0.47}As$ previously reported [17]. The spectrum is dominated by an intense peak close to the GaAs-like LO phonon frequency. This peak is broader than the GaAs-like LO phonon mode of $In_{0.53}Ga_{0.47}As$ and displays a slight asymmetric broadening towards the high energy side, both of which are indicative of coupling with the hole plasma. The Raman spectrum of undoped $In_{0.53}Ga_{0.47}As$ shows a broad mode labeled R^* at ∼ 244 cm^{-1} that was assigned to a disorder mode [17]. The contributions of both the R^* mode and of the GaAs-like LO phonon mode from the surface depletion region were estimated from a four-Lorentzian fit to the spectra, and are plotted in Fig. 1 with dotted and dash-dotted lines, respectively. To account for the lattice disorder associated with doping impurities and alloying, an asymmetric Lorentzian with a low-frequency tail was used to fit the GaAs-like LO phonon peak. The asymmetric line shape with a low frequency tail arises from scattering by disorder-activated modes with wave vectors $q \neq 0$ in the dispersive LO branch. A weaker Raman peak is also observed at ∼ 229 cm^{-1} close to the frequency of the InAs-like LO phonon mode.

With increasing hole concentration, the strong peak at the GaAs-like LO frequency vanishes and only a weaker, narrower peak that corresponds to the uncoupled GaAs-like LO phonon mode from the surface depletion region is detected. Concurrently, the peak close to the InAs-like LO phonon frequency shifts to lower frequencies and increases in intensity. At the highest hole concentrations (samples *C* and *D*), an additional peak is resolved at ∼ 260 cm^{-1} between the disorder mode R^* and the GaAs-like LO phonon mode, which also shifts to lower frequencies with increasing carrier density. The carrier-density dependence of the Raman

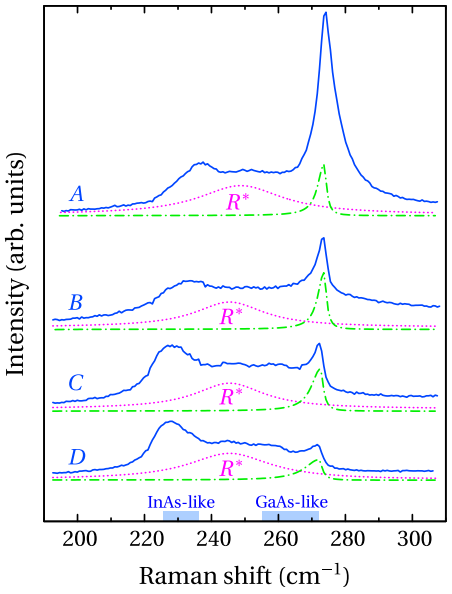

Fig. 1. Raman spectra of *p*-$In_{0.53}Ga_{0.47}As$ layers with hole concentrations of 2.2×10^{17} cm^{-3} (A), 2.7×10^{18} cm^{-3} (B), 1.2×10^{19} cm^{-3} (C), and 2.4×10^{19} cm^{-3} (D) obtained at 80 K in $x(yz)\bar{x}$ configuration. The contributions of the disorder mode R^* and of the GaAs-like LO phonon mode from the surface depletion region are indicated by dotted and dash-dotted lines, respectively. The light-blue shaded areas on the frequency axis correspond to the regions between the TO- and LO-phonon frequencies of each alloy sublattice.