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F. Plentz, E. A. Meneses, F. Meseguer, and J. SánchezDehesa

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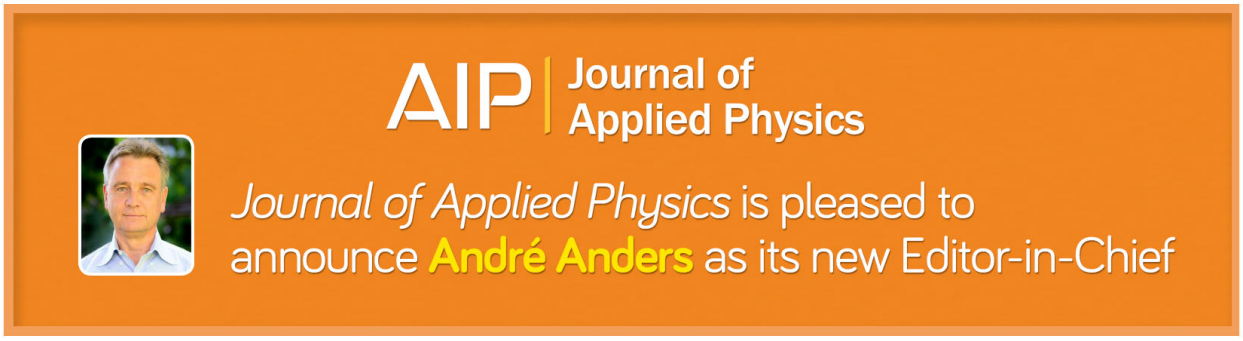

New $Al_xGa_{1-x}As$ related deep luminescence observed in modulation doped quantum wells

F. Plentz and E. A. Meneses[a)]
Instituto de Física "Gleb Wataghin," Universidade Estadual de Campinas, C.P 6165, 13081-970 Campinas, Brazil

F. Meseguer and J. Sánchez-Dehesa
Instituto de Ciencias de Materiales de Madrid (C.S.I.C.) and Instituto de Ciencia de Materiales "Nicolas Cabrera" (U.A.M.), Facultad de Ciencias (C-IV), Universidad Autónoma, 28049 Madrid, Spain

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An emission band that appears in the high energy side of the photoluminescence spectra of a modulation doped multiple quantum well structure was investigated by means of magneto-photoluminescence and photoluminescence excitation spectroscopy. We show that this emission band is related to the $Al_{0.36}Ga_{0.64}As$ layers of the structure. We analyze the data within the framework of the configuration coordinate model and attribute this photoluminescence band to the recombination of electrons trapped to a new deep center in the alloy and the photogenerated holes.© *1995 American Institute of Physics.*

I. INTRODUCTION

The problem of silicon (Si) incorporation in $Al_xGa_{1-x}As$ epitaxial layers is one of the most studied in the field of GaAs related technology.[1] This is due to the fact that achieving high quality n-doping is fundamental to improve the performance of GaAs/$Al_xGa_{1-x}As$ based devices.[1,2] Photoluminescence (PL) has been widely used to study and characterize the Si doping of this material.[2–8] It is well known that Si incorporates in $Al_xGa_{1-x}As$ giving rise to at least two energy states in the alloy band gap.[1,9] One is the usual shallow donor state and the other the so called DX center that is responsible for the persistent photoconductivity effect (PPC).[10]

In the past few years several works have reported luminescence peaks associated to Si complexes in this alloy.[2,3,6–8] In this paper we report on a PL band observed in the high energy side of the fundamental transition of an asymmetric Si modulation doped multiple quantum well structure (n-MDQW). By performing magneto-photoluminescence (MPL) and photoluminescence excitation spectroscopy (PLE) measurements we show that this emission is associated with a new deep center located at the $Al_xGa_{1-x}As$ layers of the structure. We explain the origin of this emission within the framework of the configuration coordinate model.

II. EXPERIMENT

The sample studied in this work is a 15 period n-MDQW. Each period has the following structure: 20 nm undoped GaAs quantum well followed by a 18.5 nm undoped, 5.5 nm silicon doped (1.2×10^{18} cm^{-3}), 40 nm undoped $Al_xGa_{1-x}As$ (x=0.36). A schematic draw of the quantum well structure and confining potential along the growth direction is shown in the inset of Figure 1. The MPL spectra is taken at 2 K in a 13 T superconducting magnet with Faraday configuration, being the magnetic field is perpendicular to the layers. The PL and PLE spectra are obtained using a He refrigerated cryostat. We use a Kr^+ pumped LD700 dye laser , an Ar^+ pumped R6G dye laser, or the 5145 Å line of an Ar^+ laser to excite the sample during the experiments. Afterwards, the PL signal is analyzed by a double monochromator and detected by using standard photon-counting techniques.

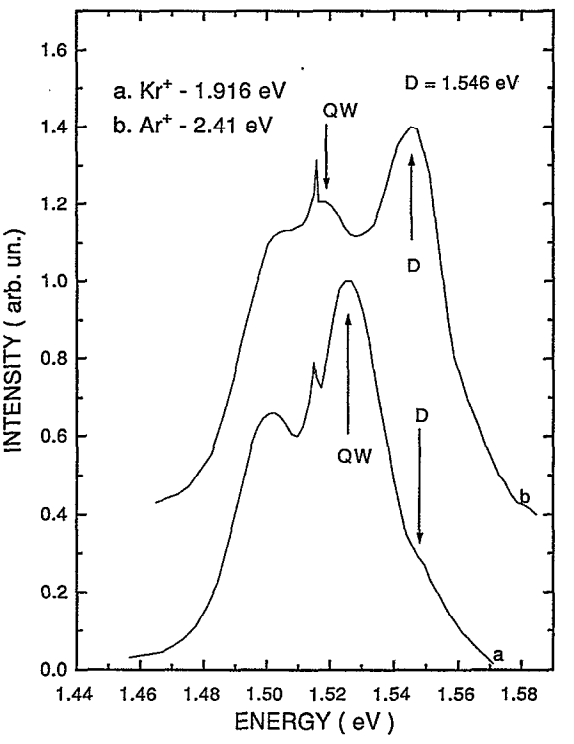

FIG. 1. Photoluminescence spectra for photons having energies below (spectrum *a*) and above (spectrum *b*) the alloy band gap. Note the increase of the band D intensity for above band gap excitation.

[a)]Electronic mail: menezes@unicamp.ifi.br

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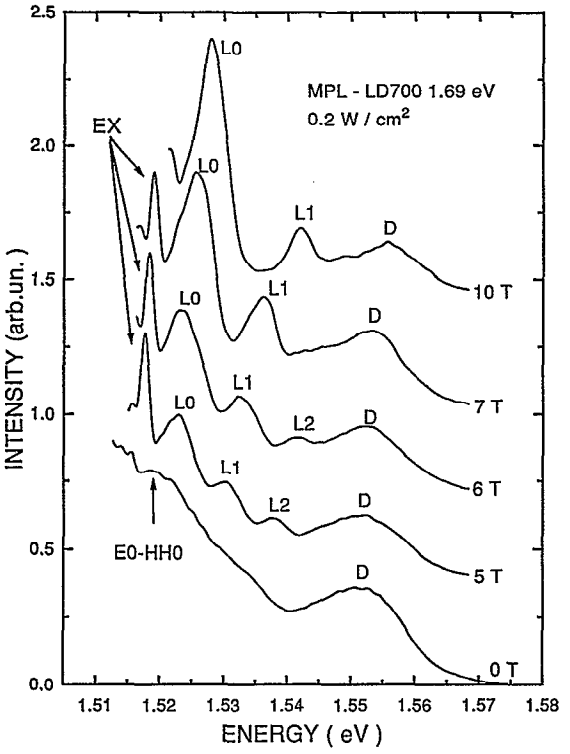

FIG. 2. Magneto photoluminescence spectra for representative magnetic field values. The excitation is done with an energy well bellow the $Al_xGa_{1-x}As$ band gap. Ex is the GaAs exciton line. The splitting of the n-MDQW related $\underline{QW}$ emission is clearly seen.

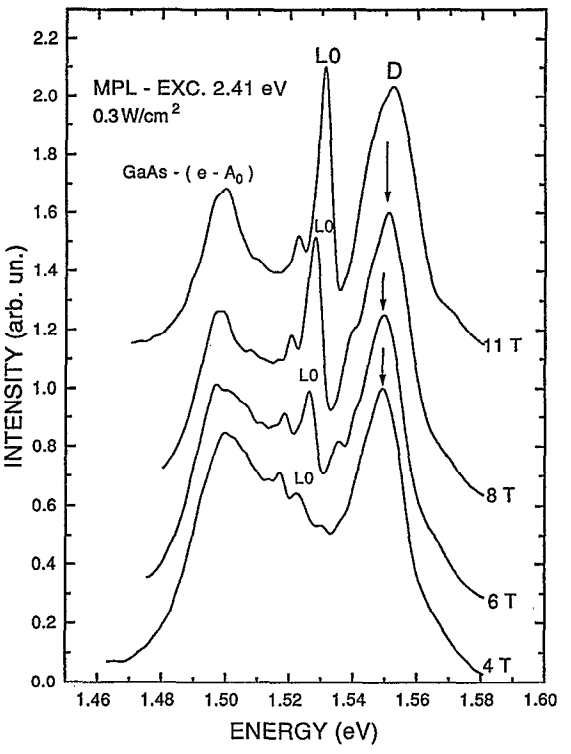

FIG. 3. Magneto photoluminescence spectra for representative magnetic field values. The excitation is done with an energy well above the $Al_xGa_{1-x}As$ band gap. Band D is the dominant spectral feature for low magnetic fields and does not show the expected behavior for a transition originating from the n-MDQW's.

III. RESULTS AND DISCUSSION

In Figure 1 we show the low temperature PL spectra taken under low excitation conditions (0.3 W/cm^2) with photons having energies below (spectrum $\underline{a}$) and above (spectrum $\underline{b}$) the alloy band gap. The peak named $\underline{QW}$ is due to the fundamental (E0-HH0, first electron sub-band to first heavy hole sub-band) transition[11,12] originating from the n-MDWQ's. The narrow peak appearing in both spectra is due to excitonic recombination at the bulk GaAs portion of the sample. The band named $\underline{D}$ located at the high energy side of the $\underline{QW}$ luminescence is the one we shall focus our attention on. It is worthy to note the remarkable increase of peak $\underline{D}$ intensity when the sample is excited with photons having an energy greater than the alloy band gap. This peak was previously attributed[11] to the n-MDQW's E1-HH0 transition which is allowed due to band bending effects.

In order to clarify the band $\underline{D}$ origin we have done MPL measurements for excitation with energies above and below alloy band gap. The spectra for some representative magnetic field values are shown in Figures 2 and 3. We observe in Figure 2 (below band gap excitation) the n-MDQW Landau levels (LLs) transitions[12] L0, L1 and L2 emerging from the $\underline{QW}$ emission (E0-HH0) as the field is increased. This is the expected behavior for a two dimensional electron gas under a magnetic field applied perpendicular to the sample. The two dimensional electron and hole sub-bands split into LLs and recombination occurs between them. The initial states are the LLs generated from the first electron sub-band (E0) and occupied by the 2DEG. The final states are the LLs related to the first heavy hole sub-band (HH0) and filled by photoexcited holes.

As the magnetic field, B, is increased; the LLs energies and their density of states increase linearly with B. Also, the LLs with higher index became empty by transferring electrons to the lower ones. The lines corresponding to these transitions move towards higher energies losing intensity. It is also expected that the line corresponding to the fundamental transition (L0) becomes narrower and more intense due to the change in the density of states induced by the applied field and the extra carriers transferred from upper LLs. All these effects are clearly observed in Figure 2 for the lines originating from the QW emission (L0, L1 and L2). Note that at high fields only the L0 transition can be observed. In contrast to this, the $\underline{D}$ emission band behaves differently as a function of the magnetic field increases. We observe neither LL transitions emerging from band $\underline{D}$ nor change in its line shape or intensity . The only effect to remark is a small blue shift of its peak energy.

The behavior of this peak, obtained using a laser energy larger than the alloy band gap can be observed more clearly in the PL spectra shown in Figure 3. The unique observed effect of the magnetic field on band D is, as put forward in the previous discussion, a small shift towards higher energies. It should be noted that if emission D was related to the second populated electron sub-band, a remarkable diminution of its intensity would be expected as magnetic field was

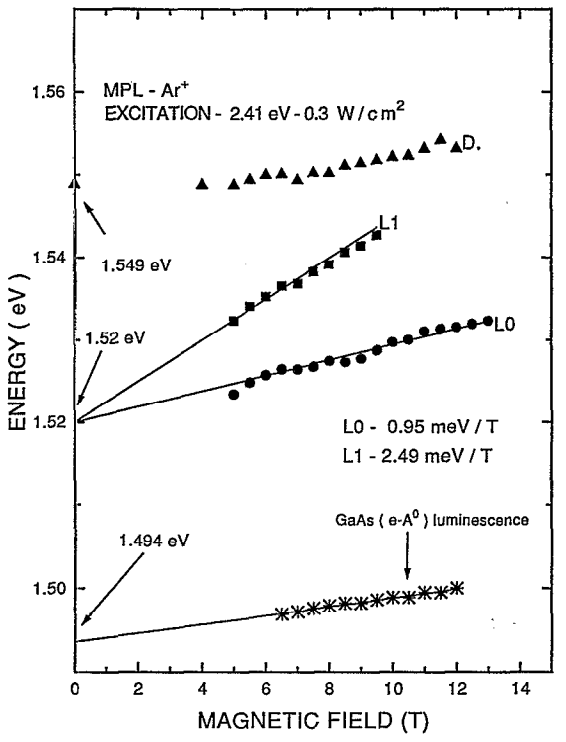

FIG. 4. Peak energy versus magnetic field plots for the transitions observed in the spectra shown in Fig. 4.

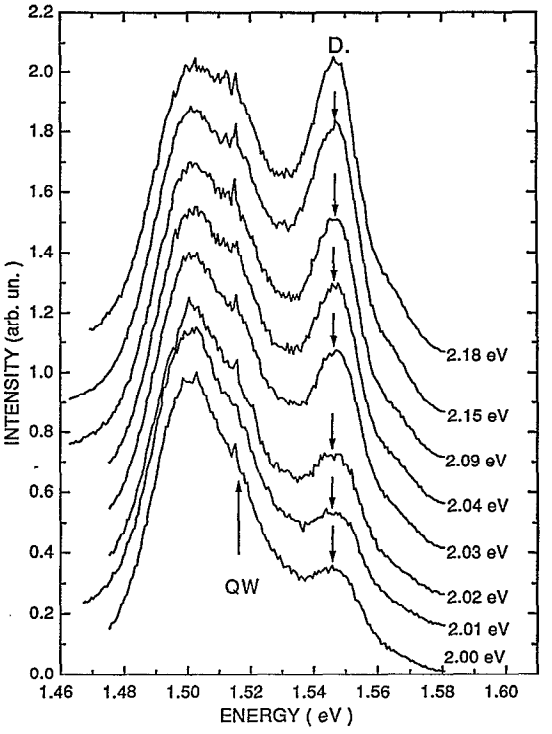

FIG. 5. Luminescence spectra taken under different excitation energies. The increase of peak $\underline{D}$ intensity can be observed as the excitation energy increases. For the higher excitation energy (2.18 eV) it is the most intense emission.

raised. On the other hand, the effects of the magnetic field on the transitions originating from the n-MDQW's are brightly seen. Note that at high fields the n-MDQW related L0 transition became the dominant spectral feature. These facts are a strong indication that band $\underline{D}$ is neither related to the second electron sub-band nor to any other transitions originated in the well of the n-MDQW's.

In Figure 4 we show the peak energy position versus magnetic field plot for the peaks obtained from the spectra is taken under Ar^+ excitation (Figure 3).The LO and L1 peaks converge at 0 T to the renormalized n-MDQW band gap and have slopes in agreement with the electron and heavy hole effective masses. We also plot the GaAs related free to bound transition involving carbon acceptors. Besides the fact that band $\underline{D}$ converges to an energy not corresponding to a n-MDQW transition, it has a slope of 0.35 meV/T, much less than that expected for a transition involving two-dimensional electron- hole recombination.

To give additional insight into the origin of band $\underline{D}$ we have measured the PL spectra for several excitation energies, which are shown in Figure 5. We can follow, step by step, the increase of band $\underline{D}$ intensity as the excitation energy is increased. From the PLE spectrum, obtained with the spectrometer at 1.55 eV and shown in Figure 6, we extract a photoexcitation onset of 2.02 eV, very close to the expected $Al_{0.36}Ga_{0.64}As$ band gap. Considering these facts and those discussed before we can affirm that this band is related to the $Al_{0.36}Ga_{0.64}As$ layers of the structure. We attribute this band to a transition between a Si related deep level and the valence band. This corresponds to a state with a binding energy of 470 meV measured from the $Al_{0.36}Ga_{0.64}As$ conduction band minimum.

In Figure 7 we present a configuration coordinate model that accounts for the origin of this emission and the fact that it is present even for excitation with photons having an energy bellow the alloy band gap. The model is based on the generation of holes on the valence band through the absorption of light by higher lying vibrational states of the deep impurity center, and the recombination of electrons trapped to center with these photogenerated holes. An incident photon of energy $h\nu_{ex}$, lower than the alloy band gap energy, promotes an electron from the valence band to a higher lying vibrational state of the impurity center. An electron trapped to the center recombines with the hole left on the valence band emitting a photon with energy $h\nu_l$. This is the observed luminescence. When the sample is excited with above band gap photons the generation of holes is largely increased giving rise to the enhancement of deep center luminescence.

We can find a theoretical explanation for the origin of this deep level by analyzing a calculation performed by Yamaguchi.[13] In that work the scattering-theoretic method is used to calculate the the defect energy levels of the alloy $Al_xGa_{1-x}As$ as a function of the defect potential $\Delta E(s_\alpha)$ for some values of the bond length relaxation Δd. Thus, by considering a silicon atom substitution on a gallium site, $\Delta E(Si_{Ga}) = -2.5$ eV, the author uses $\Delta d = -0.3$ Å in order to fit the experimental data for the standard DX center binding energy ($E_{CB} - E_{DX} \approx 170$ meV). Now, if we take the de-

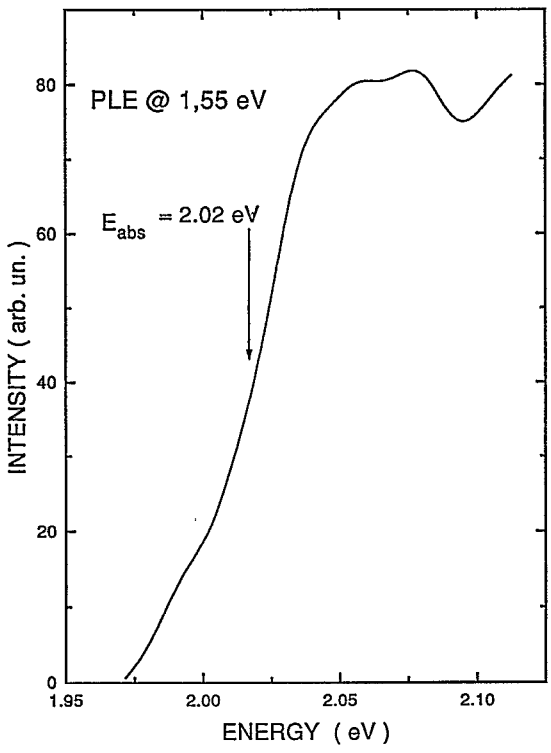

FIG. 6. PLE spectrum for the band $\underline{D}$. The photoexcitation onset is compatible with the expected band gap for the $Al_{0.36}Ga_{0.64}As$ alloy.

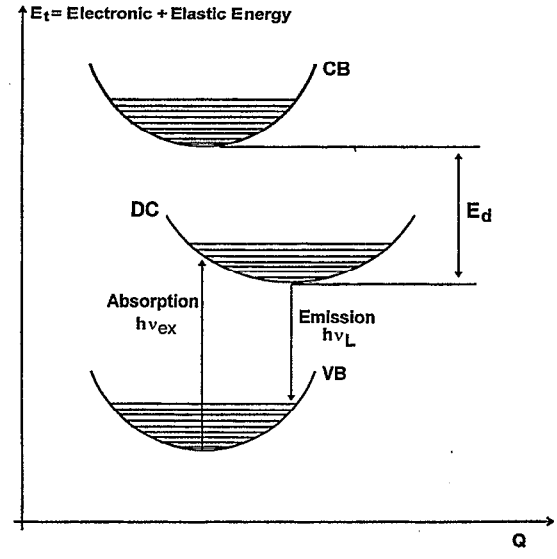

FIG. 7. Representation of the configuration coordinate model for the deep center (DC) responsible for band $\underline{D}$ emission. Q is the lattice coordinate and E_t the total energy (electronic + elastic) of the system. The measured binding energy E_d is 470 meV.

fect potential expected for a silicon atom substitution on an aluminum site, $\Delta E(Si_{Al}) = -3.2$ eV, and the same Δd we find a binding energy of around 400 meV. This value is compatible with the one observed by us for deep center which is responsible for the D band emission. Let us remark that the calculated energies are very sensitive to the bond relaxation (see Fig. 4 of Ref. 13), and therefore, the measured deep center energy is obtained if one consider a smaller value of this parameter. In fact, it is worth quoting the recent work by Yamaguchi and Junnakar,[14] which also proposes a small lattice relaxation picture of DX.

IV. CONCLUSIONS

In conclusion, we attribute the observed emission to a DX center originating from a substitutional Si atom in an Al site. This interpretation is consistent with the measured slope of a linear fit to the peak energy position versus magnetic field plot for band D. As the deep state has a very small magnetic field dependence of its binding energy, we observe only the energy shift corresponding to the change in the energy of the final state of the transition, i.e., the $Al_{0.36}Ga_{0.64}As$ valence band.

This mechanism of generation of holes in the $Al_{0.36}Ga_{0.64}As$ layers of the structure proposed is the one responsible for the decrease in the n-MDQW two dimensional electron gas density when the sample is excited by photons having an energy lower than the alloy band gap.[12]

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