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Microelectronics Journal 35 (2004) 59–61

Microelectronics Journal

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Spectroscopic ellipsometry of intentionally disordered superlattices

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Abstract

We characterized the electronic properties of ordered and intentionally disordered GaAs–$Al_xGa_{1-x}As$ superlattices, with and without dimer-type correlations in the disorder, by means of spectroscopic ellipsometry in the near band-edge region. The spectra have been compared to the calculate electronic structure. The optical transitions in the various superlattices show specific features related to their different electronic structure.
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Keywords: Photoluminescence; Superlattices; Ellipsometry

Photoluminescence (PL) and vertical transport experiments in intentionally disordered semiconductor superlattices (SL's) proved to be useful tools to provide a clear validation that spatial correlations of the disorder lead to electron delocalization of states in SL's [1,2], as previous theoretical calculations suggested [3], in contrast to the earlier belief that all eigenstates might be localized. To provide further confirmation of these conclusions, in the present work we report on spectroscopic ellipsometry (EL) of ordered and intentionally—uncorrelated and correlated—disordered GaAs–$Al_{0.35}Ga_{0.65}As$ SL's. Thus, we extend previous results reported by other authors concerning dielectric and optical properties of ordered GaAs–AlAs SL's [4].

We present a physical interpretation of the EL spectra in the energy region close to the near band-edge optical transitions on the basis of their different electronic states. We characterized three undoped SL's grown by molecular beam epitaxy. All the SL's have 200 periods and $Al_{0.35}Ga_{0.65}As$ barriers 3.2 nm thick. In the ordered SL (OSL) all the 200 wells are identical with thickness 3.2 nm (hereafter referred to as A wells). In the random SL (RSL), 58 A wells are replaced by wells of thickness 2.6 nm (hereafter referred to as B wells) and this replacement is done randomly. The so-called random dimer SL (DSL) is similar to the RSL with the additional constraint that the B wells appear only in pairs [3]. Every SL is clad on each side by 100 nm of n-$Al_{0.3}Ga_{0.7}As$, Si doped to 4×10^{18} cm^{-3}, with a 50 nm n-GaAs buffer layer (doped to 4×10^{18} cm^{-3}) on the substrate and a 3 nm n-GaAs cap layer (doped to 6×10^{18} cm^{-3}).

EL spectra at room temperature have been recorded with a rotating-polarizer spectroscopic ellipsometer, with variable incidence angle, in the spectral range between 1.4–5.0 eV. The spectra reported in this work were measured with an incidence angle of 75°, i.e. close to the Brewster angle of the $Al_{0.3}Ga_{0.7}As$ alloy. PL at room temperature have been measured in order to facilitate the interpretation of the EL spectra (PL spectra at low temperature were reported in Ref. [1]).

Fig. 1 shows the real part ε_1 of the pseudo-dielectric function in the region of the near-band edge optical transition. In the upper panel of Fig. 1, well resolved transitions, not masked by noise, are detected around 1.6 eV. In the lower panel we report on the PL spectra of the same samples, showing that the energy of the radiative transitions match the EL features mentioned above. We also found that the interband optical transitions of the SL's are not well resolved in the imaginary part ε_2 of the pseudo-dielectric function. Therefore, ε_1 is found to be much more sensitive to the inter-miniband transitions, and consequently it will be the focus of our interest hereafter.

In Fig. 2 we show on the same plot the ε_1 spectra of the three SL's (right axis corresponds to the OSL while the left one corresponds to both random SL's). Regarding the OSL we can attribute the change in the slope (marked by the two dashed lines and labeled MB) of the ε_1 spectrum at 1.595 eV, to the inter-miniband transition threshold, being

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doi:10.1016/S0026-2692(03)00223-4

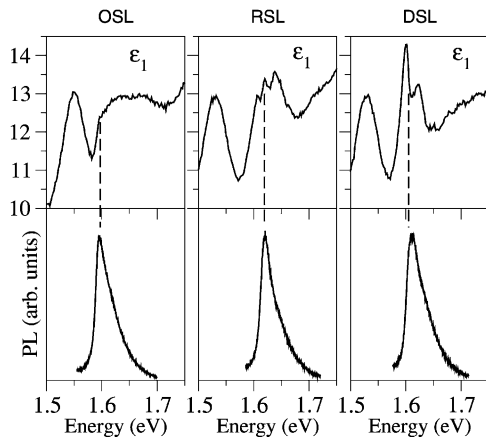

Fig. 1. Real part ε_1 of the pseudo-dielectric function of the three SL's (upper panel) and room temperature PL spectra (lower panel) close to the near band edge.

in perfect agreement with the PL spectra. On the contrary, both intentionally disordered SL's (RSL and DSL) present well resolved maxima at different energies. The structure labeled e(A) at 1.62 eV are resolved in both spectra (see the upper curves in Fig. 2), while the maximum denoted by e(B) at 1.64 eV arises only in the RSL. Finally, a peak below e(A), labeled DB, is clearly resolved in the EL spectrum of the DSL, while it is absent in the RSL. The energy of the maximum DB is about 5 meV above the inter-miniband transition threshold of the OSL (labeled MB in Fig. 2).

To elucidate the origin of the various transitions we carried out a theoretical study of the SL's [3], based on the envelope-function approximation within a one-band model, which is known to be accurate enough in wide-gap SL's with thick layers. The main results of the calculations done at $T = 0$ K are shown in Fig. 3. As it has been shown by Fujiwara [5], the red shift of the near band-edge optical transition in the OSL is due to the formation of a miniband due to coherent tunneling processes between the wells (left panel). On the contrary, transitions involving localized

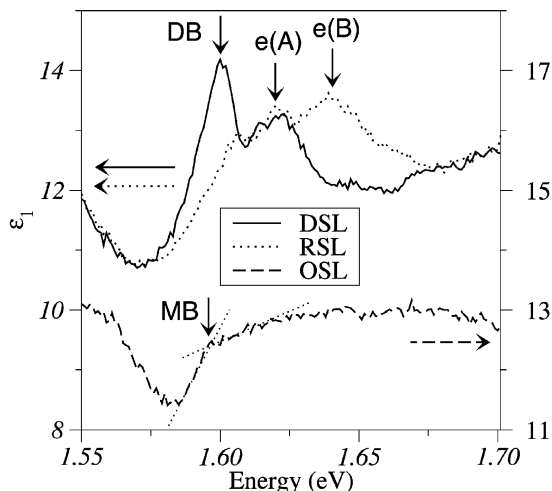

Fig. 2. Real part ε_1 of the pseudo-dielectric function of the three SL's. In the OSL spectrum the dashed lines indicate the change in the slope of ε_1.

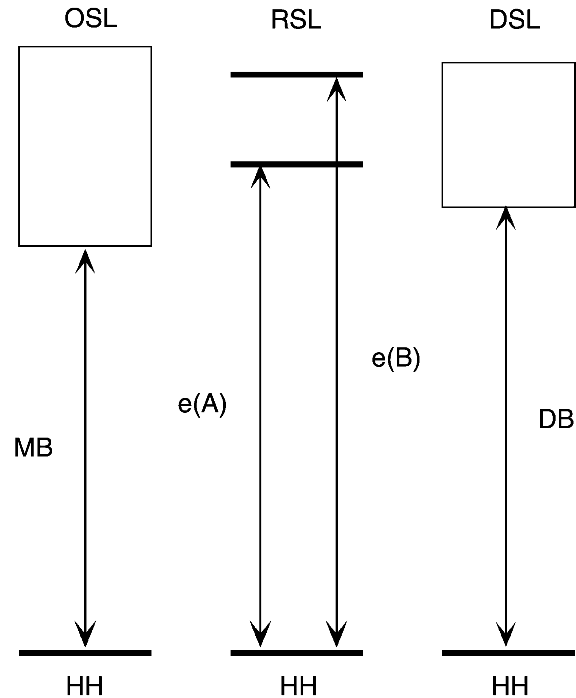

Fig. 3. Schematic view of the transitions between the heavy holes in the valence band and the electronic states in the conduction band of the SL's.

states at A and B wells arise in the RSL (middle panel). At low temperature, the DSL is characterized by a band of extended states, which also may yield a red shift of the transition energy (right panel). It should be mention that temperature effects are stronger in disordered SL's [1], so a quantitative comparison is meaningless.

The feature MB in Fig. 1 should be at lower energy than the transitions involving electronic states of the isolated A wells (left panel of Fig. 3). Transitions related to isolated wells are resolved in the EL spectra of the RSL since electron states are spatially localized due to Anderson localization. The structure labeled e(A) at 1.62 eV can be attributed to inter-band transitions between electrons and heavy-holes in the wide A wells. Moreover, the maximum denoted by e(B) at 1.64 eV is attribute to inter-band transitions the narrow B wells (see middle panel of Fig. 3). These features are separated by 20 meV, in agreement with the calculated energy difference between the ground state levels of isolated A and B wells, which is found to be 22 meV. The PL spectrum is peaked nearly at the same energy of the e(A) transition, indicating that the PL is mainly due to recombination from this level. A small shoulder is observed in the PL spectra at 1.64 eV, corresponding to the e(B) feature.

The EL spectrum of the DSL shows a peak at 1.60 eV, which is red shifted with respect to the transition in the RSL at 1.62 eV. This red shift is also revealed in the PL spectra at room temperature (Fig. 1) as well as at 4 K [1], and provides further support to our previous theoretical calculations and experiments about the occurrence of a band of delocalized

states in correlated disordered SL's [1,3]. This claim is corroborated from the absence of transitions e(B) arising from isolated B wells, indicating that the coherence length is larger than the SL period even at room temperature.

The ε_1 lineshapes of the three SL are clearly different in this region of the near band-edge transition. The lineshape is closely related to the oscillator strength and, consequently, depends on the particular electronic structure of each SL [1–3]. The OSL and DSL present band of extended states while in the RSL all the states are localized, as theory [3] and experiments showed [1,2]. Therefore, the arrangement of electronic levels responsible of the optical transitions depends on the SL considered (OSL, RSL, or DSL).

In conclusion, we have studied the fundamental optical transition of ordered, random and random-DSL's by means of EL and PL spectroscopies. These near-band edge optical transitions result in different EL lineshapes arising from and evidencing the different electronic structure of the SL's.

Work at Madrid was supported by DGI-MCyT (Project MAT2000-0734). V.B. was partially supported by MURST (Project 'Giovani Ricercatori').

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