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Experimental evidence of delocalization in correlated disorder superlattices

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Abstract

We studied GaAs–$Al_{0.3}Ga_{0.7}As$ intentionally disordered semiconductor superlattices with and without correlation of the disorder. The structural properties have been characterized by X-ray diffraction. The electronic states of the SL have been studied by photovoltage spectroscopy and compared with theoretical calculation of the miniband structure and transmission coefficient. We observed that delocalization processes take place when the disorder is correlated, confirming the theoretical expectations.

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Keywords: Superlattices; Correlated disorder; Anderson localization

1. Introduction

In last decade a number of disordered one-dimensional (1D) models have been proposed which exhibit non-trivial extended states [1–3]. This phenomenon is due to a particular spatial correlation of the disorder, which is the fact that defects appear always in pairs, i.e. never isolated. Further research in this and related models supported this interesting result, including other grouping rules aside form pairing [4–8]. This intriguing phenomenon has been recently theoretically foreseen and experimentally verified using semiconductor superlattices (SLs) [9]. Really in these systems the electrons experience a low-dimensional potential, and the high control on the growth reached by the molecular beam epitaxy which is usually used to produce these systems, allows the construction of intentionally disordered potential profiles with a structural correlation of the disorder. Additionally, since there has been many theoretical and experimental works in disordered SLs related to localization electronic effect

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[10–14] appeared reasonable to study experimentally this process of electron delocalization in these kind of materials [15]. In this work we present a study of the structural and electronic properties of intentionally disordered superlattices with and without spatial correlation of the disorder. The structural properties of semiconductor SLs are usually investigated by X-ray measurements. From the analysis of the rocking curves information on the period thickness and composition of the SLs, and information about periodicity and disorder can be obtained [16]. In order to study optically the superlattice photocurrent (PC) and photovoltage (PV) spectroscopy is often used [17]. This technique gives the possibility to investigate the energy separation within SLs miniband as well as the perpendicular transport mechanisms which determine the temperature and electric field dependence of the photocurrent. In this work we measured PV spectra of our SLs embedded in the intrinsic region of a n–i–n structure.

2. Experimental details

The samples are n^+–i–n^+ structures grown by molecular beam epitaxy (at temperatures between 550°C and 600°C) for which the intrinsic region is the undoped SL. A 100 nm thick $Al_{0.3}Ga_{0.7}As$: Si (doped to 4×10^{18} cm^{-3}) is grown on n^+–GaAs substrate and then the SL is grown onto this layer. Finally, a 100 nm thick $Al_{0.3}Ga_{0.7}As$: Si (doped to 4×10^{18} cm^{-3}) and a 3 nm GaAs : Si cap layer (doped to 6×10^{18} cm^{-3}) are grown on the top of the whole structure. All the SLs have 200 periods and $Al_{0.35}Ga_{0.65}As$ barriers 3.2 nm thick. In the ordered SL all the wells are identical, of thickness 3.2 nm. These will be referred to as A quantum wells. In the random SL 58 wells of 3.2 nm (which correspond to the 30% of the total number of wells) have been replaced with wells 2.6 nm thick (referred to as B quantum-wells) and the replacement has been done at random. Lastly, the random dimer SL is identical to the random SL with the additional constraint that B wells appear only in pairs. In this sample the disorder exhibits the wanted short-range spatial correlation. In Fig. 1 we report the schematic view of the conduction-band for the three SLs.

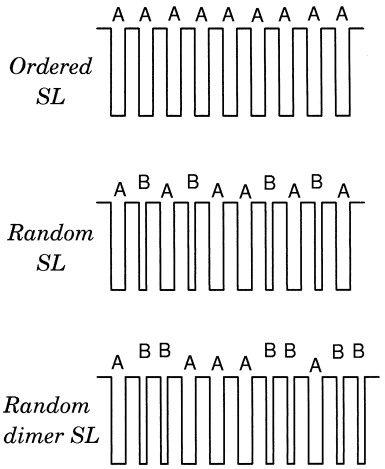

Fig. 1. Schematic conduction-band profile of the superlattices.

The rocking curves have been measured by a double crystal X-ray diffractometer. The electronic states of the SLs have been characterized by PV spectroscopy; the spectra have been measured at different temperatures in the range 10–200 K, although in the present work only the 10 K spectra are commented, and with a spectral resolution of 0.18 meV.

3. Results and discussion

Firstly, the structure of the as grown sample has been characterized by X-ray diffraction measurements. Double crystal X-ray diffraction rocking curves for the 004 symmetric reflection of the random SL and random dimer SL samples are reported in Fig. 2. The spectra show that the angular position of the SL satellite peaks is perfectly the same for the two samples, indicating that the two SLs have the same period [16]. Thus, the only difference between the two samples is the pair correlation intentionally introduced during the growth.

It has been possible to measure PV in our structures although there is not any intentional junction. In our structures little potential barriers take shape between the n^+ and n regions giving rise to measurable PC and PV signals. These PC and PV signals, measured without external field applied, have the same spectral

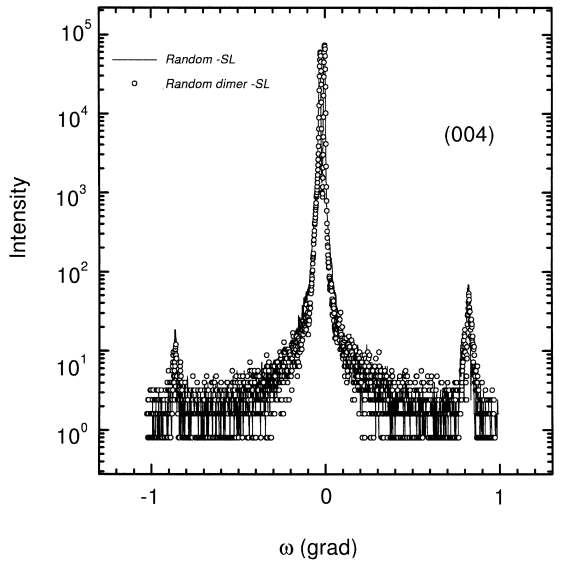

Fig. 2. X-ray rocking curves of the random and random dimer-SLs.

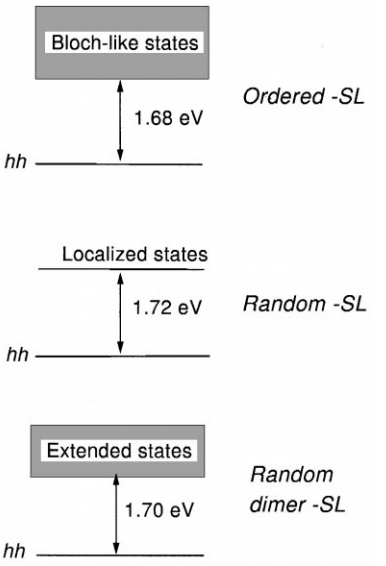

Fig. 4. Schematic view of the miniband structure of the three SLs.

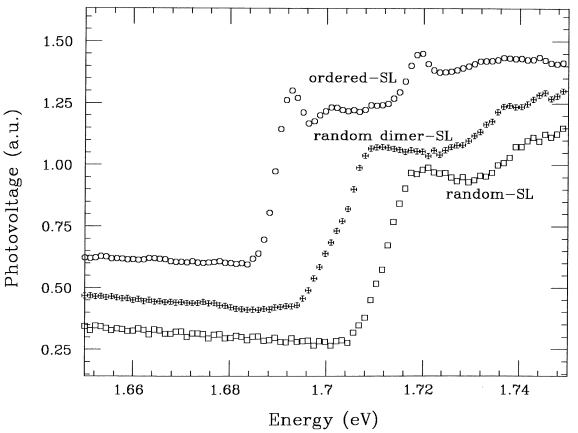

Fig. 3. Photovoltage spectra of the ordered, random and random dimer SLs at the temperature of 10 K.

behavior. Their intensity has a spectral dependence that directly reflects the optical absorption processes between minibands. PV and PC spectra contain also information related to the perpendicular transport mechanisms that can be evidenced from a study of the spectra as a function of temperature. Work along this direction is actually in progress.

In Fig. 3 we report the photovoltage (PV) spectra of the three samples at the temperature of 10 K. In the PV spectrum of the ordered SL we can see at 1.69 the rise up of the absorption with the associated heavy-hole excitonic peak. We calculated the miniband position of the SL using a Kronig–Penney method with Γ effective masses $m_e^* = 0.067$ for GaAs and $m_e^* = 0.096$ for $Al_{0.35}Ga_{0.65}As$. Fig. 4(a) shows a schematic view of the conduction miniband obtained from the calculations. The miniband in the conduction band of the ordered SL lies in the range between 1.68 and 1.76 eV, measured form the very narrow heavy-hole miniband. These values well agree with the PV spectrum, being the experimental position of the PV threshold very close to the lowest energy of the miniband. As regards the random SL, we found that the whole PV spectrum is shifted to higher energies (see Fig. 3) with respect to the spectrum of the ordered SL. In the random SL the intentional disorder, given by the random distribution of B wells, localizes the electron states [9,15]. The calculated energy for the transitions between electron and hole states is now 1.72 eV, in good agreement with the experimental position of the PV absorption threshold. The PV spectrum of the random dimer SL moves to lower energies with respect to the spectrum of the random SL, and the absorption threshold is at energy comprised between the one of the ordered SL and that of the random SL. This red-shift of the electron transition energy with respect

to the disordered SL is due to the formation of a miniband of extended states with tunneling of the electrons between GaAs wells [17]. This result give evidence of the formation of a band of extended states due to the structural correlation of the disorder. According to theoretical studies, [15] these extended states are not Bloch-like, as occurs in ordered SLs. Thus, we calculated the transmissions coefficient for the electrons with the method of Ref. [15] and we found a band of extended states with a minimum at 1.70 eV with respect to the very narrow heavy-hole miniband [9]. This value is in good agreement with the experiment, being equal to the energy position of the PV threshold of the random dimer SL. The PV signal rises from the transport process of carriers generated by the optical absorption mechanism; in our disordered SLs the interplay between these two processes could account for the reduction of the excitonic peaks. As a summary of the theoretical calculations of the electron miniband in the three SLs, we report their schematic view in Fig. 4.

The electronic states of these superlattices were studied also by photoluminescence, and the results of these experiments were reported elsewere [9]. The energy of the PL of the three SLs at 10 K is practically the same than those observed now in PV spectra. The relative position of the PL was observed to be almost independent on temperature up to room temperature [9] indicating that these transitions are little modified by the phonon interaction. The agreement between the optical spectra both in emission (PL) and in absorption (PV) is a good confirmation of our interpretation of the experiments.

4. Conclusions

In conclusion, we experimentally studied, in a comparative way, the electronic states of ordered, uncorrelated-disorder and correlated-disorder SLs. X-ray diffraction rocking curves shown that the dimer-type correlation was the only difference between the random SL and random dimer SL. PV experiments show the presence of a delocalization process for the electrons when the intentional disorder of the potential profile is correlated. The calculation of the electronic structure is in agreement with the experimental data.

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