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Local Incorporation of Lateral Piezoelectric Fields in Strained III/V Semiconductor Nanostructures

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We demonstrate the local incorporation of piezoelectric fields in III/V semiconductor heterostructures via the concept of lateral piezoelectric fields. Our theoretical discussion and experimental results underline the huge potential of artificial semiconductor crystals with engineered piezoelectric properties for nonlinear-optical applications as well as for sensing and actuating devices.

The proper design of intelligent (smart) materials and structures is one of the most important future challenges in the interdisciplinary field of physics, materials science and engineering. Piezoelectric materials form an excellent basis for the development of intelligent structures comprising sensors and actuators which can actively react to an unpredictable environmental disturbance in an controlled manner. For an optimum performance the discrete actuators should be located at distinct sites of the structure. In this paper we report on the incorporation of lateral piezoelectric fields in strained InAs/GaAs- heterostructures and quantum wells (QW) with high spatial resolution. Our exploration is based on the finding that a strong piezoelectric polarization exists in strained InAs QW on GaAs substrates with non-[100] orientation. In general this polarization is composed of a normal and a parallel component. In ideal InAs/GaAs QW without any lateral structuring only the polarization component normal to the interface generates polarization charges and piezoelectric fields. As yet research has been devoted exclusively to these vertical fields[1, 2, 3]. In a patterned quantum well, however, the lateral polarization component also introduces polarization charges and hence piezoelectric fields.

In this work we first discuss the main properties of these lateral piezoelectric fields. Then we demonstrate the local incorporation of these lateral piezoelectric fields in (110) InAs/GaAs - quantum wire structures. Our data not only underline the huge impact such fields can have on the optical properties of semiconductor heterostructures but also show the possibility to construct actuators and sensors functionable on a nanometer scale.

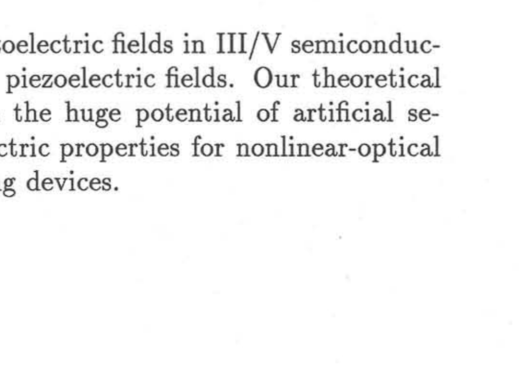
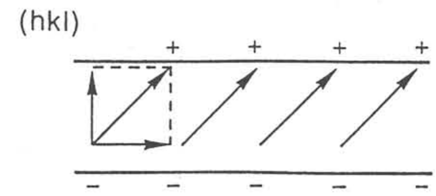


FIG. 1: Magnitude of the piezoelectric polarization vector in a pseudomorphically strained InAs-layer on GaAs substrates of various orientations.

We use solid-source molecular beam epitaxy (MBE) to synthesize our structures on (110) and (100) GaAs substrates. All samples are characterized carefully using high-resolution double crystal X-ray diffraction (HRDXD). For the photoluminescence (PL) experiments the samples are mounted in an optical flow-through cryostat at 6 K and excited by the red line (647.1 nm) of a Kr^+ laser. Figure 1 gives the magnitude of the piezoelectric polarization vector in a strained InAs layer on GaAs substrates of various orientations. The polarization disappears for the high-symmetry [100] orientation and takes its maximum value for (111) structures and remains close to the maximum for orientations between [111] and [110].

As illustrated by fig. 2 the piezoelectric polarization $\vec{P}$ in general splits up in a lateral and a vertical component, i. e. a component parallel and a component perpendicular to the interfaces. In an ideal quantum well only the vertical polarization component produces electric charges and therefore electric fields.



$$\vec{P} = \vec{P}_{\perp} + \vec{P}_{\parallel}$$
$$\vec{E} \propto \vec{P}_{\perp}$$

FIG. 2: Piezoelectric polarization in a strained quantum well of [hkl] orientations.

However, as illustrated in fig. 3, we can unleash the lateral polarization component by a lateral patterning of the quantum well interfaces. In this way we allow the polarization vector to "pierce" the interface and to create piezoelectric charges and the corresponding electric fields. The nature of lateral fields and their consequences for the potential profile of a heterostructure can be best understood by considering a special example. We select a strained (In,Ga)As quantum wire structure on (110) GaAs with the wires running in [01$\bar{1}$] direction. The piezoelectric polarization in the strained (In,Ga)As wires points in [001] direction and therefore creates charges on the wire edges. Figures 4(a) and (b) show the potential profile of the quantum wire array with and without piezoelectric fields. The presence of piezocharges leads to a bending of the bands inside the (In,Ga)As quantum wires and to a somewhat lesser extent even outside the wires in the unstrained GaAs barrier. The presented modification of the potential profile by the lateral piezoelectric fields has a dramatic impact on the energy levels of the wire array as well as the optical matrix elements.

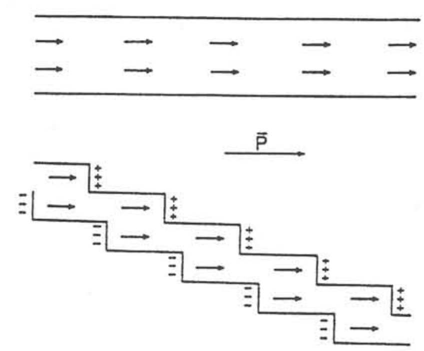


FIG. 3: In an ideal heterostructure with unpatterned interfaces the lateral component of the polarization does not give rise to electric fields. This can be changed by an artificial patterning of the interfaces which introduces piezoelectric charges and fields.

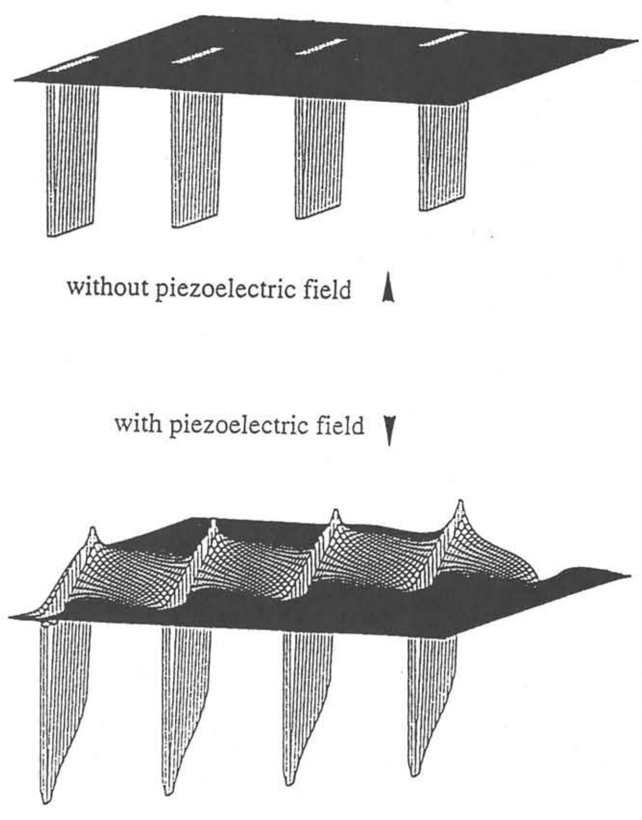


FIG. 4: Potential surface of a [01$\bar{1}$] cross-section through a (110) $In_{0.5}Ga_{0.5}As$ quantum wire structure with and without lateral piezoelectric fields. The wire width is 200 Å and the thickness 4 Å.

Such wire structures can be realized on vicinal (110) GaAs surfaces which tend to facet during epitaxial growth[4]. By an appropriate choice of the misorientation angle it is possible to create a lateral structure with a period on the scale of a few hundred Å[5]. For the present experiments a miscut of the (110) substrates of 7° towards (111) was selected. These values make the creation of polarization charges possible and - as demonstrated by high-resolution electron microscopy [6] - provides a lateral period with an appropriate value of approximately 300 Å.

Figure 5 shows PL spectra taken from a series of (100) and (110) InAs/GaAs samples with different values for the thickness of the InAs layers. The spectra of the (110)-samples exhibit an extremely strong dependence on the excitation density whereas the (100) spectra remain virtually independent of this parameter. The blue-shifts of the (110) PL lines range from a few meV in sample #1(110) to 22 meV for sample #2(110). This observation contrasts with a shift of zero in the (100) reference samples. It can be understood by the presence of strong internal electric fields in the (110) samples.

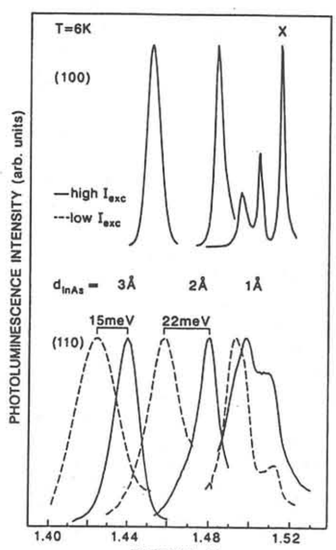


FIG. 5: PL spectra for (110) and (100) samples. For the (110) samples #2 and #3 the spectra are taken at an excitation density of 3 mW/cm^2 and 30 W/cm^2 whereas for sample #1 excitation densities of 3W/cm^2 and 30 mW/cm^2 were used.

Also in strong contrast to the (100) case, we observe a reduction of the PL linewidth with increasing excitation density. An increase of the PL linewidth with increasing electric field strength is a familiar feature of standard (100) heterostructures under external electric fields[7]. We therefore assign the linewidth reduction observed here to the screening of the internal piezoelectric fields by photogenerated carriers.

With blueshift and linewidth reduction upon increase of the excitation density we thus observe two features which strongly imply the presence of internal electric fields in our (110) samples. These results indicate that we have achieved the local incorporation of piezoelectric fields on a nanometer scale. Based on these experimental results in combination with our theoretical considerations we therefore conclude that these materials form a suitable starting point for the synthesis of microsensors and -actuators. Furthermore the strength of the observed effects underlines the potential of lateral piezofields for nonlinear optical applications.

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