Acoustic Nanostructures for Charge Carrier Confinement in $GaAs/Al_xGa_{1-x}As$ Multiple Quantum Wells

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Quantum confinement of charge carriers in semiconductors is at the heart of next generation energy conversion technologies, as well as new encryption and computation paradigms. We propose a novel approach that uses picosecond-duration surface acoustic phonon pulses to produce lateral carrier confinement (2D and 3D confinement) in III-V (i.e. polar) semiconductor quantum wells. Strain generated by the phonon pulses varies with depth below the sample surface (Fig. 1), locally deforming the valence and conduction bands to produce lateral confinement in the plane of a quantum well. This approach offers the prospect of continually modifying confinement in a manner that can be externally controlled. Using molecular beam epitaxy, we grew the GaAs/AlGaAs structure in Fig. 2, consisting of three quantum wells of width 5, 7, and 10 nm, buried beneath the sample surface at depths of 14, 49, and 112 nm respectively. These wells are positioned so as to coincide with different conditions of shear strain and dilatation, and hence piezoelectric field strength (Fig. 1). [1] We characterize the optical properties of the quantum wells with photoluminescence (PL).

Using our model of the strain distribution (Fig. 1), we calculate band deformations, and hence the red shift in the band gap energy.[2] Due to the piezoelectric moduli of GaAs, we observe a confinement regime in which electrons and holes are separated into adjacent valleys and peaks of the lateral piezoelectric potential, suggesting a relation between luminescence lifetime and carrier confinement. We will present results from preliminary studies showing carrier transport at the speed of sound in the sample with extended lifetimes due to acoustic confinement. This approach could find useful applications in nanocircuitry.

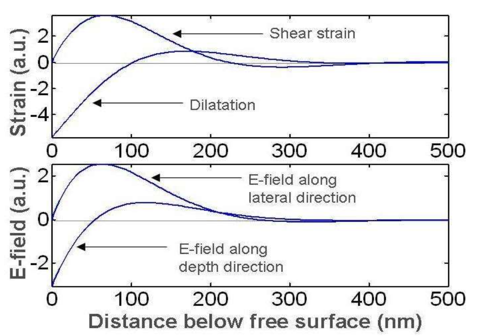

Figure 1: Variation of strain (top) and piezoelectric field amplitude (bottom) in the sample growth direction.

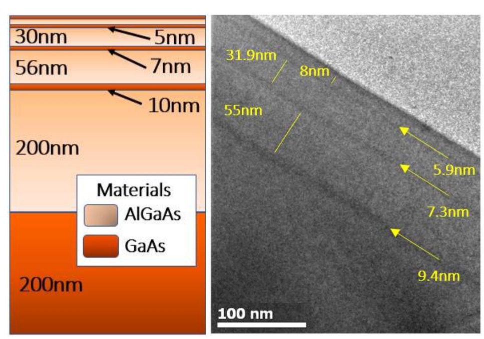

Figure 2: Left: GaAs/AlGaAs multiple quantum well structure. Top two layers 9 nm and 5 nm. Right: TEM of grown sample. The dark stripes correspond to the GaAs QWs.

[1] D. Royer, E. Dieulesaint, J. Acou. Soc. Am. **76**, 1438(1984). [2] K. Kash, Phys. Rev. Lett. **67**, 1326(1991).

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Supplementary Information

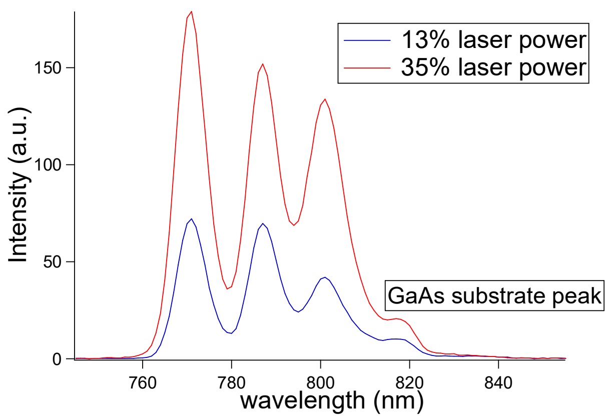

Figure 3: 7K Photoluminescence spectra of the GaAs/AlGaAs multiple quantum wells. The pump wavelength was 532nm.

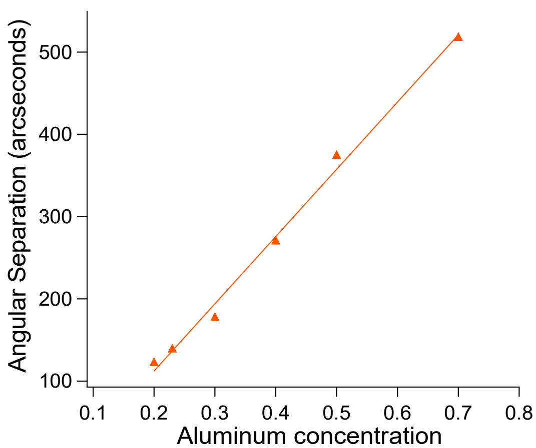

Figure 4: X-ray diffraction of different $Al_xGa_{1-x}As$ bulk samples with compositions x = 0.2–0.7.

PL measured at 7K shows the GaAs substrate peak at 814 nm, and the subsequent peaks at 800 nm, 787 nm and 771 nm, corresponding to the three quantum wells (Fig. 3). The increasing peak intensity at shorter wavelength is consistent with the narrowest quantum wells being closest to the sample surface.

To control the barrier heights and hence adjust the confinement, we carefully calibrated the $Al_xGa_{1-x}As$ composition using x-ray diffraction (Fig. 4). The linear relation between the angular separation of the AlGaAs and GaAs diffraction peaks, and the Al concentration, indicates precise control over the AlGaAs barrier height.

There are two confinement regimes relevant to this study, related to the scale associated with the structure (L) relative to the exciton-Bohr radius (R): the weak and moderate confinement regimes. In the weak confinement regime ($L>R$) we look at the acoustoelectric field disassociating the exciton, resulting in a quenching of the PL peak. In the moderate confinement regime ($L\sim R$), we observe the acoustoelectric field changes the location of the exciton PL peak, and influences carrier relaxation pathways. We can gauge the strength of the confinement modulation (i.e. the acoustoelectric field amplitude) in the weak confinement regime by measuring the laser fluence (i.e. phonon amplitude) required to quench the exciton PL peaks.

We verify carrier confinement and transport using two identical suboptical wavelength absorption gratings to generate and detect surface acoustic phonons. Placing metallic gratings on the surface of the sample helps modulate the absorption of light on a length scale that is smaller than the optical diffraction limit. This provides us a spectrally selective generation scheme for surface acoustic phonons with wavelengths in the 20 – 200 nm range. We observe that the shorter wavelength end of this range is comparable to length scales typically associated with quantum confinement. We also anticipate remote detection of short wavelength surface acoustic phonons, opening the door to future experiments that will investigate dynamic strain modification of electronic properties in regions that are within the propagation path of the phonon wavetrain and adjacent to the generation grating.