Linear and quadratic electro-optic coefficients of self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots

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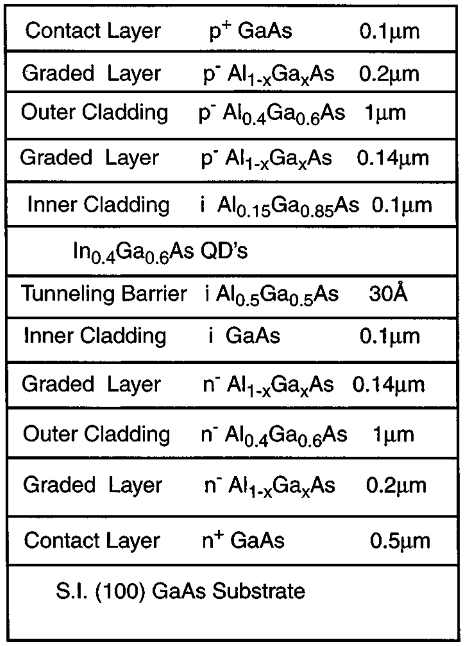
The electro-optic properties of self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots have been studied experimentally. Single-mode ridge waveguide structures were grown by molecular beam epitaxy with self-organized $In_{0.4}Ga_{0.6}As/GaAs$ quantum dots in the guiding region. The measured linear and quadratic electro-optic coefficients are 2.58×10^{-11} m/V and 6.25×10^{-17} m^2/V^2, respectively, which are much higher than those obtained for bulk GaAs or quantum well structures. The measured transmission characteristics indicate that low-voltage amplitude modulators can be realized with quantum dot active regions. © *1998 American Institute of Physics.* [S0003-6951(98)01511-3]

Nonlinear optical materials are attractive for their use in optical devices such as switches and electro-optic and electro-absorption modulators. Bulk III–V compounds such as GaAs and GaAlAs exhibit a linear electro-optic (Pockels) effect since they are noncentrosymmetric and lack inversion symmetry. However, the effect is weak compared to that in crystals such as lithium niobate. From the point of photonic integrated circuits, it would be very useful to realize nonlinear electro-optic devices, which could be integrated with other active and quasiactive devices such as lasers, detectors, and interferometers. A great deal of work has therefore been done to investigate the optical properties of quantum wells and superlattices.[1] Quantum wells demonstrate enhanced electro-optic effects due to two features: a built-in birefringence due to the layered structure and a quadratic electro-optic (Kerr) effect arising from the quantum confined Stark effect (QCSE) near the excitonic absorption edge.[2] Low-dimensional quantum confined structures such as quantum wires and dots are expected to exhibit enhanced optical nonlinearities and enhanced electro-optic effects.[3–9]

Various techniques for realizing quantum wires and dots have been reported in the last decade. Quantum structures can be formed by epitaxial growth of quantum wells followed by fine-line lithography, etching, and regrowth—conceptually the most straightforward process—but the results are not very encouraging. In particular, in quantum dots the surface-to-volume ratio can be very large and the resulting nonradiative recombination through surface and interface states can severely degrade the optical properties.[10,11] Other techniques of fabrication have also not been very successful due to dot size nonuniformity or poor interface quality.[12–16] Nonetheless, we did report the measured enhancement of electro-optic effect in small (25–35 nm diameter) $In_xGa_{1-x}As/GaAs$ ($x=0.1$ and $x=0.15$) etched dots.[3] The observed photoluminescence from the dots was very weak and the phase-retardation measurements proved to be difficult. Self-organized growth of strained heterostructures has emerged as a very successful technique for realizing small and defect-free quantum dots with good optical properties.[17–21] Room-temperature lasers with self-organized quantum dots in the active region have been reported recently.[22–24] In this letter, we report the measurement of the electro-optic coefficients of the $In_{0.4}Ga_{0.6}As/GaAs$ self-organized quantum dots from the observed phase retardation in single transverse mode waveguides induced by a transverse electric field. To the best of our knowledge, this is the first report on the electro-optic properties of self-organized quantum dots.

A quantum dot heterostructure was grown by molecular beam epitaxy (MBE), as shown in Fig. 1. The active layer consists of a single layer of self-organized $In_{0.4}Ga_{0.6}As$ quantum dots with a GaAs layer grown over it. The growth conditions are described elsewhere.[23] The grown heterostructure, in fact, forms an edge emitting laser which is suitable for electro-optic measurement. The 30 Å $Al_{0.5}Ga_{0.5}As$ layer is used to tunnel electrons into the quantum dot and to reduce



Contact Layer	p^+ GaAs	0.1μm
Graded Layer	p^- $Al_{1-x}Ga_xAs$	0.2μm
Outer Cladding	p^- $Al_{0.4}Ga_{0.6}As$	1μm
Graded Layer	p^- $Al_{1-x}Ga_xAs$	0.14μm
Inner Cladding	i $Al_{0.15}Ga_{0.85}As$	0.1μm
$In_{0.4}Ga_{0.6}As$ QD's		
Tunneling Barrier	i $Al_{0.5}Ga_{0.5}As$	30Å
Inner Cladding	i GaAs	0.1μm
Graded Layer	n^- $Al_{1-x}Ga_xAs$	0.14μm
Outer Cladding	n^- $Al_{0.4}Ga_{0.6}As$	1μm
Graded Layer	n^- $Al_{1-x}Ga_xAs$	0.2μm
Contact Layer	n^+ GaAs	0.5μm
S.I. (100) GaAs Substrate		

FIG. 1. Schematic of the quantum dot heterostructure grown by molecular beam epitaxy.

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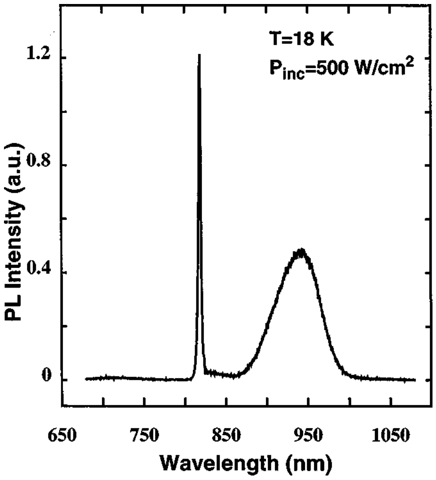

FIG. 2. Measured photoluminescence spectrum at 18 K.

hot-carrier effect when the structure is operated as a laser.[25] For all practical purposes it does not play a role in the electro-optic properties being discussed here. Cross-sectional transmission electron micrographs (XTEMs) show the dots to be pyramidal in shape with heights equal to 7 nm and base widths equal to 14 nm. A dot density of 5×10^{10} cm^{-2} is measured by atomic force microscopy (AFM). Single-mode ridge waveguides 3 μm×840 μm with both *p* and *n* contacts on the top surface were fabricated by standard photolithography, wet and dry etching, and contact metallization techniques. The diodes have leakage currents ~100 nA and reverse breakdown voltage of 12 V. Low temperature ($T=18$ K) photoluminescence (PL) measurements were made using a HeNe ($\lambda=632.8$ nm) laser, a monochrometer, a photomultiplier, and lock-in amplification. The PL spectrum is shown in Fig. 2, where two distinct peaks are observed at 1.515 eV (818 nm) and 1.315 eV (943 nm). The former originates from bound exciton recombination in the GaAs layers surrounding the dot and the latter is from recombination in the $In_{0.4}Ga_{0.6}As$ quantum dots. The peak energy corresponds to transitions involving the electron and hole ground states. It may be noted that the integrated luminescence intensity of the quantum dot transition is higher than that of the GaAs-related transition, in spite of the small dot volume.

Measurement of the electro-optic coefficients was carried out by coupling 1.15 μm light from a He–Ne laser onto one end of a 840 μm long waveguide with a focusing lens. The polarization of the light is oriented, through use of an input polarizer, at 45° to the direction of the diode electric field with an applied reverse bias. The phase retardation of the transmitted light was measured with an analyzer and a Ge detector at the output end. The measured phase retardation and refractive index change as a function of reverse bias, as shown in Fig. 3, are seen to vary with field in a nonlinear manner. The linear and quadratic electro-optic coefficients are obtained by fitting the measured phase retardation with the relation[26]

$$\Delta\Phi=\pi\, Ln_0^3\lambda^{-1}(\Gamma_l rE+\Gamma_q sE^2), \tag{1}$$

where n_0 is the average refractive index in the active region, E is the average electric field, r and s are the linear and quadratic electro-optic coefficients, respectively, and Γ_l and Γ_q are the linear and quadratic confinement factors, taking into account the fill factor of the quantum dot array. The confinement factors themselves are separated into those for the quantum dot, the GaAs layers, and the $Al_{0.15}Ga_{0.85}As$ guiding layers which are, respectively, 1.25×10^{-2}, 0.415, and 0.456. The fill factor of the dots is estimated to be 0.242 using the technique described in Ref. 27. The values of r and s obtained for the quantum dots are 2.58×10^{-11} m/V and 6.23×10^{-17} m^2/V^2, respectively. Note that the linear electro-optic coefficient is larger than that of GaAs (Ref. 28) or of GaAs- and InP-based multiquantum wells.[29–32] Similarly, the quadratic electro-optic coefficient is also very large compared to the quantum wells, in spite of a small fill factor. A multiple dot layer active region, commonly used in lasers, may yield even larger electro-optic coefficients.

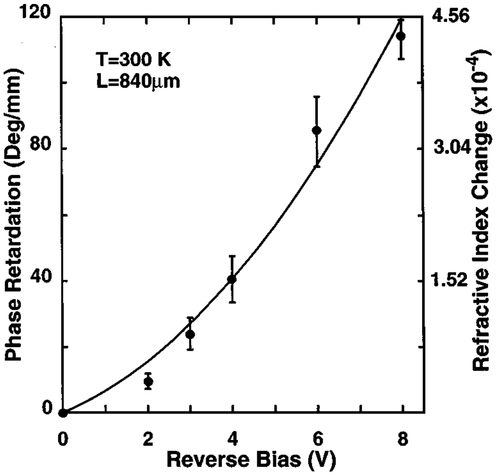

FIG. 3. Phase retardation and refractive index change as a function of reverse bias. The curve is a fit to the measured data.

The change in the phase retardation and refractive index with applied electric field strongly depends on the operating wavelength.[26] In our experiments, the separation between the excitation energy and the photoluminescence peak is 0.141 eV at room temperature. The quadratic electro-optic effect and refractive index change will be enhanced as the wavelength of the guided light approaches the quantum dot interband transition peak, but at the cost of large absorption loss. The absorption spectrum of a perfect quantum dot is ex-

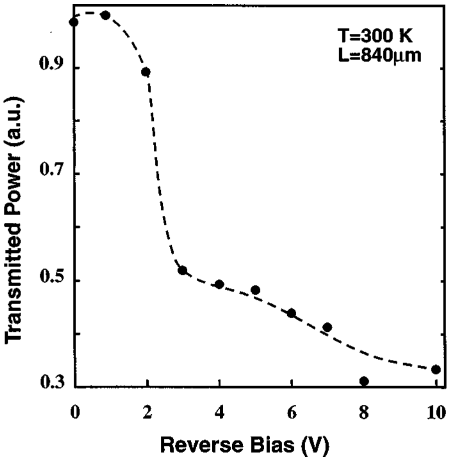

FIG. 4. Normalized transmitted light as a function of reverse bias. The dashed line is shown as a join of the measured data.

pected to be a set of sharp transitions, corresponding to the discrete bound states. Although experimentally such is not the case, a large change in the refractive index with a small absorption loss is expected. The bias-dependent transmission of the quantum dot phase modulator is depicted in Fig. 4. A large change in transmission, almost by a factor of 2, is obtained for a small applied bias of 3 V. The change in the absorption coefficient of the phase modulator due to changes in the applied electric field is obtained by fitting the power transmission with $T=e^{-\Gamma\Delta\alpha L}\cos^2(\Delta\Phi/2)$. The estimated value of $\Gamma\Delta\alpha$ is less than $7\ \mathrm{cm}^{-1}$.

In conclusion, we have measured the linear and quadratic electro-optic coefficients and phase and amplitude modulation characteristics of $\mathrm{In}_{0.4}\mathrm{Ga}_{0.6}\mathrm{As}$ single-layer self-organized quantum dots. Both electro-optic coefficients are significantly larger than those measured in quantum wells, with very small absorption loss. The results indicate that low-voltage modulators can be made with quantum dots.

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