Measurement of electro-optic coefficients of 1.3 μm self-assembled InAs/GaAs quantum dots

J. Tatebayashi, R.B. Laghumavarapu, N. Nuntawong and D.L. Huffaker

The electro-optic properties of 1.3 μm self-assembled InAs/GaAs quantum dots grown by metal organic chemical vapour deposition are reported. The linear and quadratic electro-optic coefficients are 2.4×10^{-11} m/V and 3.2×10^{-18} m^2/V^2, respectively, which are significantly larger than those of GaAs bulk materials. Also, the linear electro-optic coefficient is almost comparable to that of lithium niobate.

Introduction: Electro-optic (EO) modulators based on self-assembled quantum dots (QDs) have attracted considerable interest for their potential application to monolithic photonic devices integrated with other components under low-driving voltage owing to their enhanced optical nonlinearities and EO properties. These enhancements are due to the enhancement of the oscillator strength [1–3] caused by the complete confinement of the electrons and holes within discrete sets of the density of states [4]. So far, several groups have reported the measurement of the phase retardation characteristics of single-layer self-assembled In(Ga)As/GaAs QDs emitting at 1.0–1.05 μm [5–7], and shown much higher linear EO (LEO) and quadratic EO (QEO) coefficients than those of GaAs bulk materials at a pumping wavelength of 1.15 μm [6, 7]. In this Letter, we study the EO properties of multi-stacked self-assembled InAs/GaAs quantum dots emitting at a telecommunication wavelength of 1.3 μm by measuring the phase retardation characteristics. The LEO and QEO coefficients are 2.4×10^{-11} m/V and 3.2×10^{-18} m^2/V^2, respectively. Both of these values are significantly larger than those of GaAs bulk materials, and the LEO of InAs QDs is almost comparable to that of lithium niobate.

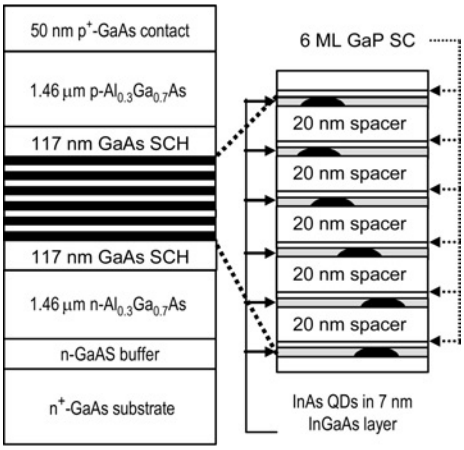

Fig. 1 *Schematic illustrations of fabricated modulator structures containing six layers of InAs quantum dots embedded in InGaAs cap with GaP strain-compensation layers*

Fabrication of QD modulators: Samples are grown by low-pressure metal organic chemical vapour deposition (MOCVD) using trimethylindium, trimethylgallium, trimethylaluminium, tertiarybutylphosphine and arsine as the source materials at a total pressure of 60 Torr. Disilane and carbontetrachloride are used as the n- and p-type doping materials. Fig. 1 shows the schematic illustration of the epitaxial structure. The QD modulator structure is grown on a (100) n-GaAs substrate followed by a 1.46 μm n-$Al_{0.3}Ga_{0.7}As$ cladding layer, the QD active region, a 1.46 μm p-$Al_{0.3}Ga_{0.7}As$ cladding layer, and a 50 nm p^+-GaAs contact layer. The doping density of n- or p-AlGaAs is 1×10^{17}/cm^3 within 0.5 μm close to the waveguide and is increased to 2×10^{17}/cm^3 for another 0.96 μm AlGaAs cladding layer. The active region consists of six stacked InAs QDs with GaP strain-compensation (SC) layers cladded by 117 nm GaAs separate confinement heterostructures (SCH). Each QD layer is grown on a five monolayer (ML) $In_{0.15}Ga_{0.85}As$ buffer, capped with 25 ML $In_{0.15}Ga_{0.85}As$, and separated by 4 nm GaAs, six ML GaP SC, and another 14 nm GaAs cap layer [8]. The density of each layer of InAs QDs is 1.9×10^{10}/cm^2. Broad area edge emitters with 100 μm-wide stripe are fabricated for measurements of the phase retardation using conventional device processing. Fig. 2 shows the room-temperature (RT) electroluminescence (EL) spectra of the fabricated QD edge emitters at various injection current densities. The separate peaks from the ground and excited states can be seen at wavelengths of 1.28, 1.22 and 1.16 μm at high injection current. Details of device characteristics of stacked InAs/GaAs QDs with GaP SC are described in [8].

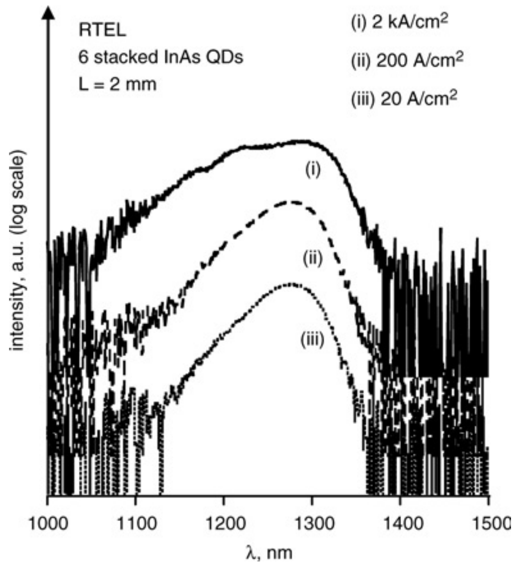

Fig. 2 *Room-temperature electroluminescence spectra of six stacked InAs quantum dot edge-emitters with GaP strain-compensation layers at various injection current densities*

Experimental results and discussion: Measurement of the EO coefficients is performed by coupling light from a distributed feedback laser onto one facet of a device with a cavity length, L, of 2 mm using an objective lens. The lasing peak of the pumping light, λ, is 1.35 μm, with detuning of 50 meV from the ground state of QDs. The polarisation of the pumping laser is oriented through use of an input polariser at 45° to the direction of the electric field applied to the device. The phase retardation of the output light from another facet propagating through the device is measured with an analyser detected by a Ge detector and lock-in amplifier.

$$\Delta\Phi = \pi L n_0^3 \lambda^{-1}(\Gamma_l r E + \Gamma_q s E^2) \qquad (1)$$

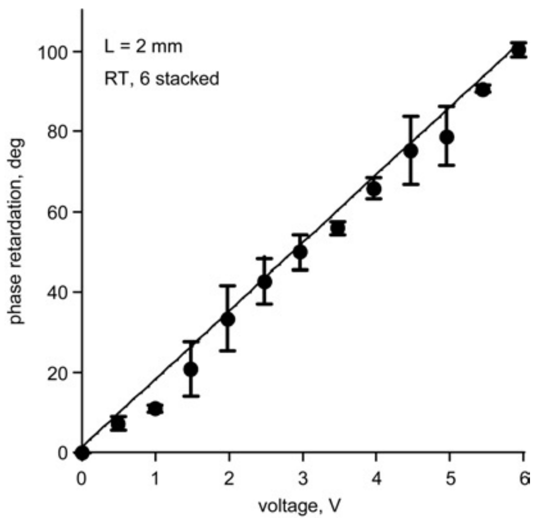

Fig. 3 *Phase retardation characteristics of six stacked InAs quantum dot modulators with 2 mm cavity length under reverse bias voltage*
——— fit to measured data

Fig. 3 shows the phase retardation characteristics of the QD modulator device against reverse bias voltage. The LEO and QEO are obtained by fitting the measured phase retardation, $\Delta\Phi$, with the relation [9] where n_0 is the average refractive index in the active region, E is the electric field in the active region which is derived from a standard depletion model, r and s

are the LEO and QEO, respectively, and Γ_l and Γ_q are the linear and quadratic confinement factor of the waveguide. The measured LEO and QEO are separated into those for QDs, GaAs matrix as

$$\Gamma_{l(q)}r(s) = \Gamma_{l(q)QD}r(s)_{QD} + \Gamma_{l(q)Matrix}r(s)_{Matrix} \quad (2)$$

where $\Gamma_{l(q)QD}$ and $\Gamma_{l(q)Matrix}$ are the confinement factors of QDs taking into account the fill factor and GaAs matrix, and $r(s)_{QD}$ and $r(s)_{Matrix}$ are the LEO (QEO) of QDs and GaAs matrix, respectively. The fill factor of the QD layer is estimated to be 0.063 using the technique described in [10]. The optical confinement factors are evaluated from the optical mode distribution, and the values of $\Gamma_{l(q)QD}$ and $\Gamma_{l(q)Matrix}$ are 1.27×10^{-3} and 0.559, respectively. The values of r_{GaAs} and s_{GaAs} are given by 1.6×10^{-12} m/V, and 1.3×10^{-20} m^2/V^2 at 1.3 µm, respectively, from [11]. The LEO and QEO of InAs QDs, r_{QD} and s_{QD}, can be derived from the measured data fitted by the equation of the relation between phase retardation and applied electric field shown above to be 2.4×10^{-11} m/V, and 3.2×10^{-18} m^2/V^2, respectively. Both of these values are significantly larger than those of GaAs bulk, and the LEO of InAs QDs is almost comparable to that of lithium niobate ($\sim 3.1 \times 10^{-11}$ m/V).

From (1) and (2) above, phase retardation characteristics largely depend on the optical confinement factor of QDs and electric field applied to the active region. It would be possible to obtain larger phase retardation under a lower bias voltage by stacking as many as possible QDs in order to increase the optical confinement factor. However, it is also required to stack QDs more densely to obtain higher applied electric field if the modulator device is operated under the same applied voltage. The use of GaP SC enables the stacking of QDs more densely and uniformly without any threading dislocations or strain accumulation since GaP SC layers can compensate the overall compressive strain within the active region which might cause threading dislocations by stacking and aggravate the device performance such as the internal loss or modal gain and so on.

Conclusions: We report the EO properties of 1.3 µm self-assembled InAs/GaAs quantum dots by measuring the phase retardation characteristics. The LEO and QEO coefficients of InAs QDs are 2.4×10^{-11} m/V and 3.2×10^{-18} m^2/V^2, respectively, which are significantly larger than those of GaAs bulk materials. Also, the LEO of InAs QDs is almost comparable to that of lithium niobate. These results would be applicable to QD-based monolithic photonic devices for fibre-optic communication systems integrated with optical components operating under a low bias voltage.

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