Efficient electroabsorption for mid-infrared wavelengths using intersubband transitions

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Abstract. We have demonstrated efficient intersubband (IS) electroabsorption in InGaAs/InAlGaAs/InAlAs step quantum wells grown by metal-organic vapor phase epitaxy (MOVPE). An absorption modulation of 2300 cm\textsuperscript{-1} at $\lambda = 5.7 \mu m$ due to Stark shift of the IS resonance was achieved with a low applied voltage swing of $\pm 0.5 \text{ V}$ in a multipass waveguide structure. Two useful wavelength ranges of $\lambda \approx 5.4-5.8 \mu m$ and $6.3-6.6 \mu m$ were obtained by considering the two flanks of the IS resonance. Based on the experimental results it is estimated that an electroabsorption modulator with a low peak-to-peak voltage of $V_{pp} = 0.9 \text{ V}$ can yield a modulation speed of $f_{3dB} = 120 \text{ GHz}$ with the present material by using a strongly confining surface plasmon waveguide of 30 $\mu m$ length.

1. Introduction
The properties of intersubband (IS) transitions in quantum wells (QWs) are attractive for application to electroabsorption (EA) modulators. One fundamental advantage is that the electron subbands run essentially in parallel such that the transition energies become independent of the wave vector. The thus peak shaped IS resonance gives a potential for strong absorption implying compact modulators. The rapid LO-phonon mediated IS relaxation time of only $\sim 1 \text{ ps}$ enables saturation resistant modulators. In simulations we have found very high $RC$-limited modulation speeds $f_{3dB}$ at low voltages \cite{1,2}, e.g. $f_{3dB} \sim 190 \text{ GHz}$ at a driving voltage of only $V_{pp} = 0.9 \text{ V}$ for a wavelength of $\lambda = 6.6 \mu m$ \cite{1}. A small IS absorption linewidth $\Gamma$ is imperative for a high $RC$-limited speed in IS-based EA-modulators, as generally the modulator capacitance $C \sim \Gamma^{-3}$ \cite{1,2}. Hence the material quality and design of the MQW is important. Recently IS transitions at the fiber-optics communication wavelength $\lambda = 1.55 \mu m$ have been demonstrated in several materials. IS based EA modulators for $\lambda = 1.55 \mu m$ are predicted to become competitive in terms of speed subject to a continued development of material quality, while also being able to handle high powers and provide a negative chirp parameter \cite{3,4}. IS transitions have primarily been applied to quantum-well infrared photodetectors (QWIPs) \cite{5} and quantum cascade lasers (QCLs) \cite{6}, and is also being researched for the application of all-optical modulators \cite{7}. IS based EA modulation has been demonstrated earlier as a proof-of-concept at mid-IR wavelengths \cite{8,9}. However these earlier demonstrations required large switching voltages of 5-10 V or more, due to the large numbers of QWs employed. In this paper efficient IS electroabsorption with a low sub-1-V

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voltage swing applied over the MQW is demonstrated experimentally. The barriers are heavily δ-doped giving a large electron concentration in the QW ground state that enables strong IS absorption. Further, the absorption coefficient in the grown MQW material is determined and the high-speed properties of a surface plasmon based modulator employing such MQW material is predicted. The structure examined here in many respects coincide with the one we previously evaluated in a modulator simulation [1].

2. Sample design

One period of the MQW structure is shown in Fig. 1. It consists of a 4 nm InGaAs well, a 6 nm InAlGaAs (nominally x_{Al}=0.25) step layer and a 17 nm InAlAs barrier layer δ-doped at n_D=2.2×10^{12} cm^{-2}. The layers are all closely lattice matched to InP and the 10 periods were surrounded by n-AlGaInAs (x_{Al}=0.37, n_D=5×10^{17} cm^{-3}) layers. The purpose of these layers is to line up the Fermi energies inside and outside the MQW without band bending in order to obtain the same IS transition energy in all step QWs [1]. IS based structures have usually been grown by molecular-beam epitaxy (MBE) owing to its better control of small layer thicknesses and lower growth temperatures which should reduce interface intermixing. The present structures were grown by metal-organic vapor-phase epitaxy (MOVPE) which is considered more suitable for mass production. The growth was performed on a semi-insulating InP:Fe substrate to minimize free-carrier absorption. To enable voltage to be applied over the structure Ti/Pt/Au contacts were deposited on the 550 nm n-InP cap layer and the 500 nm buffer n-InP layer (both doped at 5×10^{17} cm^{-3}) below the MQW stack.

3. Experimental results

The grown sample was characterized by high-resolution X-ray diffraction measurements and Hall measurements. The absorption spectra were measured using Fourier-transform infrared spectroscopy (FT-IR) with samples in a multi-pass waveguide geometry 6 mm in length (see inset of Fig. 2). Isolation of the IS absorbance was achieved by taking the ratio of the transmission spectra of TM- and TE-polarized light, A=-log_{10}(T_{TM}/T_{TE}). In addition a smooth background offset, due to the polarization dependence of the FT-IR spectrometer, was subtracted. Due to polarization selection rules IS transitions almost exclusively couple to TM-polarized light. The absorption spectra contained two peaks corresponding to the 1→2 and 1→3 IS transitions as shown in Fig. 2. The FWHM linewidth of the 1-2 IS resonance was 26 meV at room-temperature and was reduced only slightly to 25 meV at 77 K.

Both the 1-2 and 1-3 IS resonances exhibited clear Stark shifts at low applied voltages, Fig. 3. We get a sufficient Stark shift for a voltage swing as low as ±0.5 V. The criterion is here that the absorption modulation should be two times larger than the remaining absorption in the low-absorption state. This would give a modulator insertion loss of 5 dB from IS transitions in a manufactured modulator with a 10 dB extinction ratio, which is reasonable. Due to the large multipass waveguide structure there was some current through the modulator even at 77 K. The ensuing small voltage drop in the n-InP contact layers was estimated from the IV-characteristic of the device and the remaining
voltage over the MQW $V_{b,MQW}$ is indicated within parentheses in Fig. 3. After compensating for this voltage drop, the Stark shift of the 1-2 IS resonance was still about 20% lower than the simulated Stark shift. The reason for the discrepancy is likely intermixing of the interfaces.

From the measured device absorbance in Fig. 3 we further determined the MQW material absorption for purely TM polarized light (i.e. light travelling in the MQW plane) vs. applied voltage over the MQW for a range of wavelengths (Fig. 4). Note that EA is obtained on both flanks of the IS resonance as shown in Fig. 3, and that the EA is strongest on the high energy side, since the oscillator strength of the 1-2 transition is simultaneously increased when the IS resonance is blue-shifted. At 5.7 µm we get a change of absorption $\Delta \alpha = 2300 \text{ cm}^{-1}$ with a voltage swing of only $V_{PP} = 0.9$ V over the MQW. Two wavelength ranges useful for EA, $\lambda \approx 5.4-5.8$ µm and 6.3-6.6 µm, were obtained on the two flanks of the IS resonance respectively. Interband based absorption modulation results at mid-IR wavelengths are scarcely available, but should amount to a smaller absorption change. We note that the obtained absorption change $\Delta \alpha$ is somewhat larger than typically obtained by the interband quantum confined Stark effect at 1.55 µm, and further that the interband absorption in low-bandgap materials suitable for mid-IR applications is generally considerably weaker.

**Figure 2.** Absorption spectrum measured at room-temperature with no applied bias ($V_b=0$ V). Absorption peaks due to the 1-2 and 1-3 IS transitions are visible. The inset shows the multipass measurement geometry.

**Figure 3.** Intersubband absorption spectra for different applied voltages at $T=77$ K. Clear Stark shifts of the 1-2 and 1-3 IS resonances are observed. Indicated for each spectrum is the applied voltage $V_b$ and within parentheses the estimated voltage over the MQW $V_{b,MQW}$.

4. Surface plasmon modulator

To fully take advantage of the demonstrated EA another waveguide design is preferable. We have proposed [1] to use a surface plasmon waveguide to get a large optical mode overlap with the active MQW layer. The surface plasmon is then supported by the gold contact layer placed closely (~50 nm) on top of the MQW and the mode overlap of the surface plasmon with the MQW is further enhanced by a 400 nm n-InGaAs layer with high refractive index between the n-InP lower contact layer and the
MQW [1,10]. By inserting the grown MQW with the EA at 5.7 µm taken from Fig. 4, and using the indicated applied voltage swing of $V_{pp}=0.9$ V, we calculate that a modulator length of 30 µm is sufficient for an extinction ratio of 10 dB. With a ridge waveguide width of 2 µm and a driver impedance of 50 Ω an RC-limited modulation speed of $f_{3dB} = 120$ GHz is obtained. This is clearly superior to interband modulators and directly modulated lasers.

5. Discussion and conclusion

We have performed electroabsorption measurements for MOVPE-grown InP-based MQW structures with InGaAs/InAlGaAs/AlInAs step quantum wells. Stark shift of the 1-2 intersubband transition yielded an absorption change of 2300 cm$^{-1}$ in the MQW material with a low required voltage swing of $V_{pp}=0.9$ V. Based on the experimental results we estimate that a modulator structure with a surface plasmon waveguide can be as short as 30 µm and give a modulation speed $f_{3dB} = 120$ GHz. Modulators in the infrared region can become useful for optical interconnects, e.g., using Si waveguides (transmission window 1.2–6.5 µm), and for free-space communication. The present sample is not designed for the atmospheric windows 3-5 µm and 8-14 µm, as would be required for long-distance communication through air, but with the present mature materials it should be no problem to design structures for these wavelengths by modifying the well width.

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