Low-Voltage Surface-Normal InGaAsP/InP Modulator for Optical Interconnects

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Abstract— **We present a quasi-waveguide angled facet electroabsorption modulator with a contrast ratio greater than 3 dB between 1496 nm and 1506 nm for 1 V drive as well as a misalignment tolerance of 30 μm.**

The ever-increasing bandwidth of computing systems will soon require data transmission rates above that which can be supported in an electrical wiring scheme [1]. Optical interconnects have long been suggested as a solution to this problem [1-2]. In planning for these future computing systems, it is necessary to develop devices to convert electronic signals into the optical domain for transmission. The optical system must be capable of handling high aggregate data rates, perhaps utilizing the wavelength-division multiplexing techniques commonly used in long distance telecommuncations.

Semiconductor optoelectronic modulators based on the quantum-confined Stark effect [3] are attractive transmitters for this application. An ideal modulator would exhibit high contrast ratio with a low drive voltage for compatibility with future generations of CMOS circuitry. Maintaining a high contrast ratio over a large wavelength range would enable the use of uncooled laser sources or of a wavelength division multiplexed optical network. System designers desire operation at high data rates (e.g. 10 Gbps) while minimizing power consumption. As a practical consideration, fabrication in 2D arrays, integration to Si CMOS electronics, and component packaging should be simple and cost-effective.

The quasi-waveguide angled facet electroabsorption modulator (QWAFEM) provides these characteristics in a compact surface-normal device [4]. This architecture features a *p*-*i*-*n* diode surrounded on two opposite sides by smooth angled mirrors etched into the semiconductor substrate, as shown in Fig. 1. The input beam reflects off one angled mirror and impinges upon the *p*-*i*-*n* diode at a large incident angle, measured from the normal (*z*-direction).

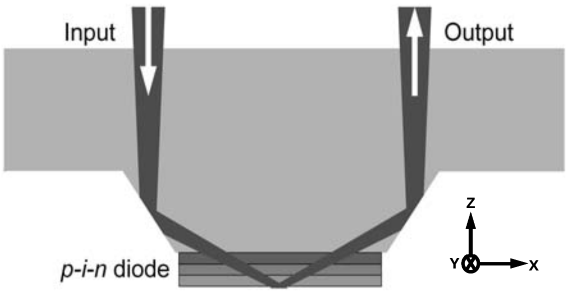

Fig. 1. QWAFEM schematic side-view (not to scale)

In order to operate at low voltage, the intrinsic-multiple quantum well (*i*-MQW) region must be kept thin. An asymmetric Fabry-Perot resonator can be designed to enhance the optical intensity of the laser beam inside the *i*-MQW region. At such a large incident angle, the InP-air interface can be used as a total internal reflector. A second (partial) reflector can be grown using alternating layers with a difference in refractive index. Note that, because of the large internal incidence angle, the reflectivity of these layers can be relatively large, even in an InGaAsP/InP system. Proper choice of layer thicknesses to align the optical resonance with the exciton peak of the *i*-MQW greatly improves the achievable contrast ratio for a low voltage drive. The combination of large internal

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incidence angle and the alignment of these resonances allows relatively large contrast with low voltage even in the long wavelength InGaAsP/InP materials system, which can have lower optical absorption than the shorter wavelength GaAs/AlGaAs system typically used for surface-normal modulators.

The wafer design was optimized using an algorithm based on a transfer matrix method and grown via metal-organic chemical vapor deposition in the InGaAsP/InP material system. Three pairs of alternating layers of InGaAsP (1.38 Q) and InP were grown as the partial reflector in the *n*-region, as shown in Fig. 2. The absorbing intrinsic region consisted of 8 lattice-matched quantum wells and the *p*-region thicknesses were chosen to allow adjustments to the resonant cavity thickness via selective etching during post-processing.

The first steps in the fabrication defined mesa structures and deposited *p*- and *n*-contacts. Next, the *n*-region was removed using an anisotropic plasma etch into the substrate in the area that was to be used for the angled facets. The fabrication of the angled mirrors was a multi-step process [5]. First, a native oxide layer was allowed to form and 40 nm of Ti was deposited as an etch mask. In the area where the angled mirrors were to be etched, the Ti was dissolved in HF:H_2O (1:100). The 90 μm-deep angled mirrors were formed by a wet etch in HBr for 24 min which reveals the (111)A plane at 54.7° from the *x*-direction. The roughness that remains on the angled facets at this point is too great (~250 nm rms) to use as a mirror. Repeated etch cycles in HBr:$K_2Cr_2O_7$ (1:1) for 1 s and HBr for 10 s resulted in smooth mirrors [5]. The rms roughness was measured to be only 1-5 nm over 60 μm areas using a Zygo white light interferometer. Finally, the cavity thickness was adjusted by selectively wet etching the top two *p*-layers, and arrays of 80 devices were flip-chip bonded with indium onto gold wires on glass substrates for testing purposes.

The reflectivity of these QWAFEM devices was measured as a function of wavelength and applied voltage using a probe station equipped with a 1550 nm tunable laser source. In order to compensate for a facet angle that deviated slightly from the designed angle (likely because of the smoothing etch procedure), the device was tilted during measurements. The contrast ratio for 1V drive was greater than 3 dB for a wavelength range of 10 nm between 1496 nm and 1506 nm (Fig. 2).

The three-bounce geometry of the QWAFEM design is tolerant to misalignment of the modulator relative to the input laser beam [4]. This feature would reduce the cost of packaging an array of QWAFEM devices in a practical system. We measured the reflectivity of the device as a function of its displacement in the *x*-direction, shown in Fig. 3. The full-width at half maximum (FWHM) was 30 μm, which is set by the lithographically-defined size of the angled mirrors.

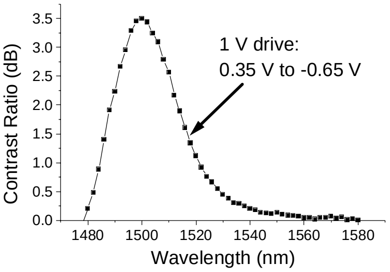

Fig. 2. Contrast ratio for a 1 V drive (from +0.35 V to -0.65 V) as a function of wavelength reaches a peak of 3.5 dB at 1500 nm in TE polarization.

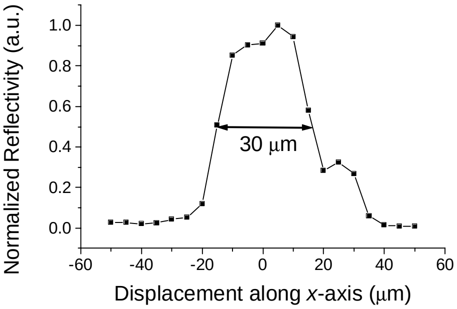

Fig. 3. Misalignment tolerance of QWAFEM device

In conclusion, we have demonstrated a surface-normal modulator with a contrast ratio greater than 3 dB over a wavelength range of 10 nm using only 1 V drive at ~1500 nm wavelength. This combination of features, along with the misalignment tolerance of 30 μm, makes the QWAFEM an attractive modulator for future optical interconnect and network systems.

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