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A Novel Optically Wide-Band Electro-Absorption Modulator based on Bandfilling in n-InGaAs

Jorn P. VAN ENGELEN[1]*, Longfei SHEN[1], Jos J.G.M VAN DER TOL[1], Gunther C. ROELKENS[1,2], Meint K. SMIT[1]
[1]Photonic Integration Research Group, Eindhoven University of Technology, The Netherlands
[2]Photonic Research Group, Ghent University – IMEC, Belgium
* j.p.v.engelen@student.tue.nl

We propose a novel membrane electro-absorption modulator (EAM) integrated on silicon. The device is based on the carrier-concentration dependent absorption of highly-doped n-InGaAs. The modulator is predicted to be wide-band and to provide an extinction ratio (ER) of 7.5 dB, an insertion loss (IL) of 1.1 dB, a modulation speed above 10 Gbit/s and a power consumption of 80 fJ/bit. The modulator has a small footprint of 10 x 120 μm^2 and operates with a 1.5 V voltage swing.

Modulators on silicon require a small footprint and a low driving voltage in order to be integrated with CMOS electronics. Conventional phase modulators are optically broadband, but have a large footprint. EAMs based on the quantum-confined Stark effect are compact, but have a narrow optical bandwidth. Therefore it would be interesting to combine the best of both: a compact, optically broadband EAM.

The EAM proposed in this paper uses the carrier-concentration-dependent absorption in highly-doped n-InGaAs. The sharp decline in the absorption of n-InGaAs with increasing electron concentration has been measured and explained with the bandfilling effect [1]. The effect on the absorption is shown in Figure 1a. Furthermore the effect covers a wide wavelength range. Recently this bandfilling effect has been used to form low-optical-loss n-type contacts [2]. In this paper modulation of the bandfilling in n-InGaAs is used to realize an EAM.

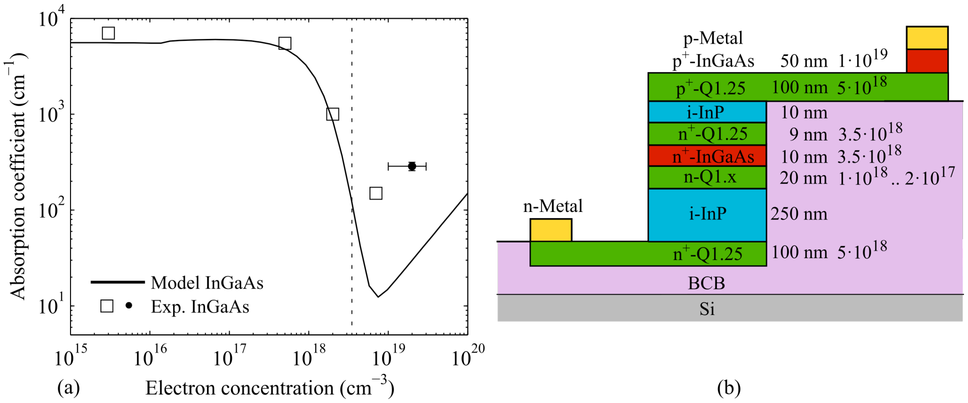

Figure 1. (a) Absorption coefficient of n-InGaAs as a function of electron concentration at 1.55 μm [2]. The doping level used in the EAM (3.5·10^{18} cm^{-3}) is indicated. (b) Proposed device structure with materials, thicknesses and doping levels [cm^{-3}] indicated.

The device is designed to be integrated in the InP-Membrane-on-Silicon (IMOS) platform [3] and to be driven by the 1.5 V voltage swing found in CMOS drivers. The use of a high index contrast membrane provides tight confinement of the optical mode and allows for double-sided processing. A typical waveguide in this platform is 250 nm high and 400 nm wide, and forms the mesa of the proposed modulator. A cross-section of the modulator is given in Figure 1b. The core of the modulator is formed by a n-InGaAs layer ($N_\mathrm{d} = 3.5 \cdot 10^{18}$ cm^{-3}) on top of the waveguide; this layer forms a p-i-n junction with the top p-Q1.25 contact layer. The doping substantially reduces the absorption of the InGaAs layer (Figure 1a). By reverse biasing the junction ($0 \rightarrow -1.5\,\mathrm{V}$), the depletion depth in the n-InGaAs layer increases which leads to higher absorption in the InGaAs layer.

Additional layers are introduced to take various effects into account. Avalanche breakdown and thermal damage due to Band-to-Band Tunneling (BTBT) current can become problematic. The 10nm i-InP between the p- and n-side causes the current due to BTBT to be sufficiently low (< 1 mA) and the avalanche breakdown voltage sufficiently high (> 6 V). Band-smoothing layers are introduced between the i-InP mesa and the n-InGaAs layer, as the large bandgap discontinuity would otherwise trap the electrons and prevent them from drifting to the n-contact at reverse bias. These band-smoothing layers are formed by four 5 nm thick quaternary layers of increasing bandgap energy: Q1.45, Q1.35, Q1.25 and Q1.15, n-type doped to $1 \cdot 10^{18}$, $5 \cdot 10^{17}$, $2 \cdot 10^{17}$ and $2 \cdot 10^{17}$ cm^{-3}, respectively. Due to the built-in potential, a depletion region is already present at 0 V. The depleted n-InGaAs has a low electron density and would therefore be absorbing, which leads to a high IL. The solution is, as is already shown in the cross-section, to replace the depleted n-region at 0 V with a non-absorbing material like Q1.25. The thickness of the quaternary layer can be tuned to make the IL very low (< 1 dB for a 120 µm long device), at the cost of slightly lower ER.

The semiconductor equations are solved in one dimension using COMSOL and verified using theoretical results based on the full-depletion approximation. The parallel plate approximation yields a junction capacitance C_j of $115..170\,\mathrm{fF}$ (for $-1.5..0\mathrm{V}$) and matches closely to COMSOL's results. The energy consumption per bit E_pb is determined to be approximately 80 fJ/bit, using $E_\mathrm{pb} = C_\mathrm{j}\, V_\mathrm{s}^2/4$ with $V_\mathrm{s} = 1.5$ V. The small-signal cut-off frequency f_c is estimated to be 11 GHz using $f_\mathrm{c} = 1/(2\pi R C_\mathrm{j})$ where R is estimated to be 100 Ω. This corresponds closely to the large signal 10%-90% rise and fall times simulated using COMSOL, which also takes into account the carrier transit time. This enables operation beyond 10 Gbit/s. Optical simulations are performed in three dimensions using Lumerical's MODE Solutions and the IL and ER are found to be 1.1 dB and 7.5 dB respectively. The optical bandwidth of the device is predicted to cover the long, conventional and short wavelength bands.

In conclusion, a novel wide-band EAM, heterogeneously integrated on silicon, is presented with a small footprint and good optical performance.

References

[1] D. Hahn, *Electron-concentration dependence of absorption and refraction in n-*$In_{0.53}Ga_{0.47}As$ *near the band-edge*, Journal of Electronic Materials, Vol. 24, Issue 10, pp 1357-1361, 1995

[2] L. Shen, *Ultra-low-loss ohmic contacts on heavily doped n-type InGaAs and InGaAsP for InP-based photonic membranes*, IEEE Photonics Journal, Vol. 8, No. 1, pp. 4500210, 2016

[3] J.J.G.M. van der Tol, *Photonic integration in indium-phosphide membranes on silicon*, IET Optoelectronics, Vol 5, No. 5, pp. 218-225, 2011