# Numerical analysis of low-temperature modulation property of III-V/Si hybrid MOS optical modulator

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**Introduction:** A Si optical modulator based on a III-V/Si hybrid MOS capacitor exhibits high-efficiency and low-loss optical phase modulation, suitable for optical interconnect in datacenter [1]. To extend the application of III-V/Si hybrid MOS optical modulator to, for example, outer-space communication and quantum computation where the operation temperature is very low, it is important to understand the low-temperature properties of the modulator. Since the III-V/Si hybrid MOS modulator uses carrier accumulation at the MOS interfaces, we expect well-behaved phase modulation even at low temperature. In this paper, we numerically analyze the temperature dependence of the modulation efficiency of the III-V/Si hybrid MOS optical phase shifter.

**Theoretical Analysis:** Since the III-V/Si hybrid MOS optical modulator utilizes the free-carrier effect in III-V and Si, the plasma dispersion effect, band-filling effect and band-gap shrinkage are taken into account [2], where the band gap narrowing with respect to temperature is considered. The temperature dependence of absorption mainly comes from the free-carrier absorption. To analyze the temperature dependence of the free-carrier absorption, the temperature dependence of the carrier mobilities are considered [3].

**Device Simulation:**

We simulate III-V/Si hybrid MOS optical modulator operating at a 1.55 μm wavelength illustrated in Fig. 1. We assume 110-nm n-InGaAsP and 220-nm p-Si layers are bonded with a 5-nm-thick $Al_2O_3$ gate dielectric [1]. The phase shifter length is set to be 500 μm. We analyze the modulation properties at the temperature range from 4 K to 400 K. Fig. 2 shows the temperature dependence of the modulation efficiency. At room temperature, the device shows the modulation efficiency of approximately 0.05 Vcm, consisting with the experimental value reported in [1]. When the temperature decreases, the modulation efficiency degrades a bit because of the lower band-filling effect. However, as we expect, the modulation efficiency at 4 K is still as high as 0.057 Vcm owing to the carrier accumulation property. The optical absorption at low temperature is expected to be reduced if we assume the low doping concentration for III-V and Si layers where the Coulomb scattering is negligible.

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**References:** [1] J.-H., Han, F. Boeuf, J. Fujikata, S. Takahashi, S. Takagi, and M. Takenaka, Nat. Photon., vol. 11, no. 8, pp. 486–490 (2017). [2] B. R. Bennett, R. A. Soref and J. A. Del Alamo, "Carrier-induced change in refractive index of InP, GaAs and InGaAsP," in IEEE Journal of Quantum Electronics, vol. 26, no. 1, pp. 113-122, Jan. 1990, doi: 10.1109/3.44924.
[3] Journal of Applied Physics 87, 2890 (2000); https://doi.org/10.1063/1.372274

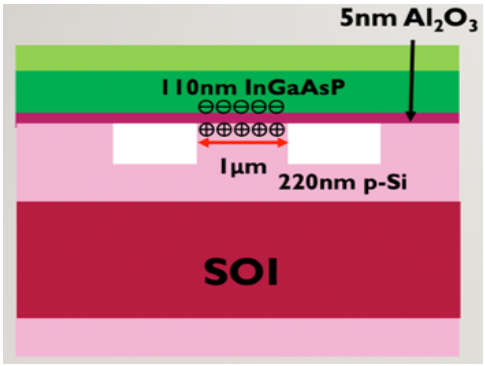


Fig. 1. Cross-sectional schematic of III-V/Si hybrid MOS optical modulator.

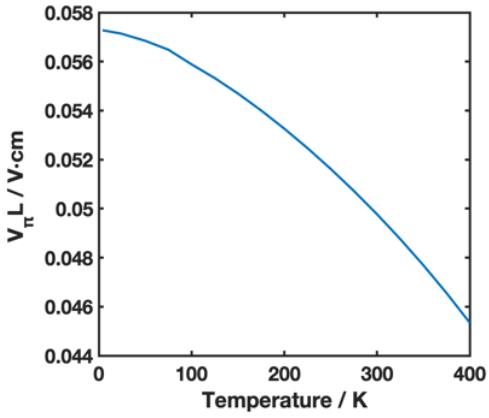


Fig. 2. Temperature dependence of modulation efficiency.