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Active Ge Based Devices for Silicon Photonics

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1. Introduction

Over the last few years active and passive photonic devices for a silicon CMOS platform have been developed [1-3]. Since III-V based materials have not yet been successfully implemented into CMOS processes, the materials options for active devices are limited. Since the development of direct epitaxial germanium growth on silicon, Ge has been widely used for near IR detectors. Due to its nearly direct band-gap, germanium has many attributes generally utilized in direct band-gap semiconductors. When considering the built-in tensile strain of the Ge layer due to thermal mismatch between Ge and Si, Ge can be used for highly effective detection up to 1600nm, covering the most important communication wavelengths.

More recently, waveguide-integrated Ge detectors deliver low dark-current, high speed, and low power consumption due the small device size that results in capacitance on the order of fF and the decoupling of absorption and carrier collection, resulting in high speed devices with >90% efficiency at 1550nm wavelength [4].

Due to its near direct bandgap behavior, Ge exhibits a strong Franz-Keldych effect that can be used for high speed signal modulation. Furthermore, high n-type doping in combination with tensile strain leads to efficient light emission from direct band gap recombination. In the following we will focus on power efficient Ge modulators and Ge light emitters.

2. Ge based EA modulators

We have developed a Ge modulator based on the Franz-Keldych effect, utilizing an electric field effect to change the absorption coefficient near the direct band gap [5]. Electro absorption modulation is inherently very fast because only the electric field is modulated and no carriers have to be moved. If the electro absorption modulation can be combined with small device size, the power consumption of such a modulator should be very low.

To ensure coupling from a single mode Si waveguide to the Ge modulator, we developed a device structure that retains single mode conditions throughout the modulator. Details of the device structure are published in [6]. This design allows efficient coupling from a Si waveguide to the modulator and back to a Si waveguide. The coupling loss for the complete structure is less than 3 dB. The modulator exhibits a DC extinction ratio of >7dB for a wide range of wavelengths. We measured an AC extinction ratio of 4dB at 1GHz, which compares very well to the AC extinction ratio of 5dB Mach-Zehnder modulators at 1GHz. The Ge modulator can potentially work at frequencies larger than 50GHz without compromising the modulation behavior.

The most significant feature of the Ge EA modulator is the ultra low power consumption. We determined that the modulator power consumption at 1GHz for 8dB extinction ratio is about 25 fJ/bit, significantly lower than for any Si based modulator. The low power consumption, combined with a low device capacitance of 11 fF, will also result in a low power modulator driver. The low power consumption is especially important for the implementation of Si photonics in devices that require a large number of photonic components.

3. Ge light emitters

The feasibility of achieving lasing in indirect bandgap materials like Ge was first discussed by Kroemer [7]. He claimed that at a sufficiently high carrier injection level, the spill-over of electrons from their lowest indirect energy valleys into the region of the smallest direct valleys allows laser action. Simulations show that a very high carrier concentration is necessary to achieve some moderate gain. Alternatively, we have theoretically shown that the small energy difference between the direct band gap and indirect band gap of Ge can be overcome by high n-type doping and tensile strain [8]. Our model shows that a strain of 0.25% is already sufficient to reach $400 cm^{-1}$ gain at an injected carrier density of $10^{19} cm^{-3}$ for an n-type doping level of $7x10^{19} cm^{-3}$.

Photoluminescence experiments on highly n-type, strained Ge show that the light emission indeed increases with doping level at room temperature [9]. Increased temperature will also increase the light emission, further verifying our model. Non-degenerate (i.e. distinct pump source and probe source) pump-probe transmittance spectroscopy measurements were performed to evaluate if gain can be reached in highly n-type Ge [10]. This experiment is used to understand optical gain from n-type Ge by studying optical absorption under pumping. For small doping levels optical bleaching can be observed that increases with increasing doping level for wavelengths shorter than 1620nm. At the currently highest experimental doping level of $1x10^{19}cm^{-3}$, optical gain of 50 cm^{-1} can be observed. For wavelengths longer than 1620nm, free carrier absorption dominates.

Conclusions

We have developed Ge based active photonic devices for implementation into Si CMOS processing. Ge based modulators show high performance over a large wavelength range exhibiting ultra low power consumption. We have also demonstrated that Ge is a promising candidate as the active material for a Si based on-chip laser. Model predictions that estimate a necessary n-type doping level of $>10^{19}cm^{-3}$ have been verified by observing net gain for highly n-type Ge.

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