resistance. In particular, the n-contact may be a significant contributor to the series resistance. It is been shown elsewhere that contact resistance to n-doped germanium can be substantially reduced by an ALD TiO_2 layer which depins the Fermi level at the interface [32]. Additionally, by reducing the device size, the distributed RC (ie., the diffusive conduction time) will also be reduced [33].

Implementing the improvements described above, it should be possible to achieve modulation rates in the tens of gigahertz. A 3 dB modulation bandwidth of 37 GHz has been previously demonstrated in 16 x 20 μm AFPMs operating at 864 nm using a GaAs/AlGaAs material system [30].

4. Conclusion

We have demonstrated asymmetric Fabry-Perot electroabsorption modulators using Ge/SiGe quantum wells grown on silicon substrates. The surface-normal configuration makes dense 2-D array integration possible, which could enable a system architecture suitable for high-bandwidth, low-power free-space optical interconnects between silicon chips. The high-speed measurements of the 60 μm diameter devices indicate substantial promise for modulation at tens of GHz in smaller devices, with energy per bit in the tens of fJ.

The relatively moderate extinction ratios ($<$ 4 dB) reported here can be further improved by better matching the top mirror reflectance to the absorption provided by the QW epitaxy at the operation wavelength. The insertion loss of the device can also be improved by changing the resonant cavity thickness to move the resonance to longer wavelengths, such that the absorption from the Ge indirect bandgap is decreased [34]. For interconnect applications, an extinction ratio of at least 7 dB is desirable, although 4 – 5 dB may be sufficient [2].

While the devices presented here operate in the wavelength range of 1400-1450 nm, the addition of silicon to the quantum wells [8] or application of strain via high silicon content barriers [35] can enable modulation at 1300 nm. Likewise, modulation in the telecommunications ”C” band around 1550 nm can be achieved by application of a DC bias, as can be seen in Fig. 1(b), or by operation at higher temperatures, since the absorption band edge redshifts by approximately $0.8\,\mathrm{nm}/^{\circ}\mathrm{C}$ [5].

The film transfer process, which involves anodic bonding to a Pyrex carrier wafer, produces chips suitable for flip-chip bonding to silicon circuits, but an alternative process is necessary for monolithic integration with CMOS circuitry. Possible approaches include the use of a double SOI wafer [36] to serve as one of the DBR reflectors [12], or performing a backside etch followed by deposition of a bottom DBR mirror [37].

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