Quantum-Confined Stark Effect Electroabsorption in Ge/SiGe Quantum Wells on Silicon Substrates

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Abstract – **We observe strong electroabsorption in Ge quantum wells with SiGe barriers, grown on Si substrates, with performance comparable to III-V materials, and promising compact, low-power, high-speed modulators compatible with Si CMOS electronics.**

Optical modulators that can be fabricated in processes compatible with silicon CMOS (complementary metal-oxide-semiconductor) electronics are very desirable for optical interconnects and links. Unfortunately, the available modulation mechanisms in Si, such as index change from free carrier plasma dispersion [1], are relatively very weak, leading to long devices [2] and/or high finesse resonators [3], and requirements for small waveguide cross-sections. III-V semiconductors have a much stronger mechanism, the quantum-confined Stark effect (QCSE) [4], which allows small and/or short modulators, including low-voltage devices without waveguides and with very relaxed alignment tolerances [5]. This QCSE mechanism is apparently absent in Si and Si-like SiGe[6], because of the different band structure of Si compared most III-V semiconductors. Here, however, we demonstrate first that Ge quantum wells with SiGe barriers, grown on SiGe buffer layers on silicon substrates, show the same quantum confinement phenomena at their direct gap as III-V semiconductors, and, second, that they show clear QCSE electroabsorption of strength comparable to that in III-V semiconductors [5]. Though Ge is an indirect gap semiconductor, the direct gap absorption is much stronger than the underlying indirect absorption tail, with the QCSE leading to absorption changes much larger than the background indirect absorption. We show absorption coefficient changes of 2800 cm^{-1}, and contrast in the absorption coefficient of > 4:1. This mechanism should allow compact, low-power, high-speed optical modulators in a Si CMOS compatible technology, with specifications comparable to good III-V devices. It promises a high-performance solution to the problem of optical output devices for silicon chips.

The structure of our sample is shown in Fig. 1. The layers are grown in a commercial reduced-pressure chemical vapor deposition reactor (RPCVD). The sample has 10 pairs of strain-balanced Ge/SiGe multi-quantum-wells (MQWs) on a SiGe buffer on a Si substrate. The quantum wells consist of strain-balanced 10nm Ge wells and 16nm $Si_{0.15}Ge_{0.85}$ barriers, on the relaxed $Si_{0.1}Ge_{0.9}$ buffer. The sample is grown as a *p-i-n* diode with the quantum wells in the *i* region, so that field can be applied to the quantum wells by reverse biasing the diode, and photocurrent can be collected.

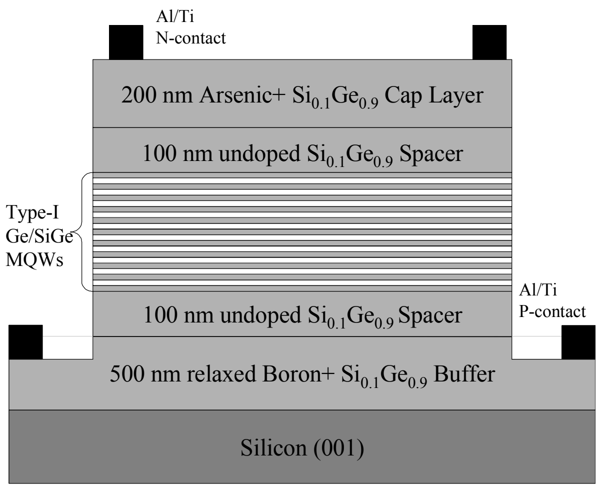

Fig. 1 . Schematic structure of p-i-n diode with Ge/SiGe MQWs grown on Si through relaxed SiGe buffer.

The compressive strain in the Ge wells will leave the heavy hole as the highest hole band. Since the zone-center direct band gaps of Si and Ge are 4.2 eV and 0.8 eV respectively, based on models of the SiGe band alignments[7], we believe our design gives strong "type-I" confinement for both electron and heavy-hole at zone center. Fig. 2 shows the expected band line-ups for our structure.

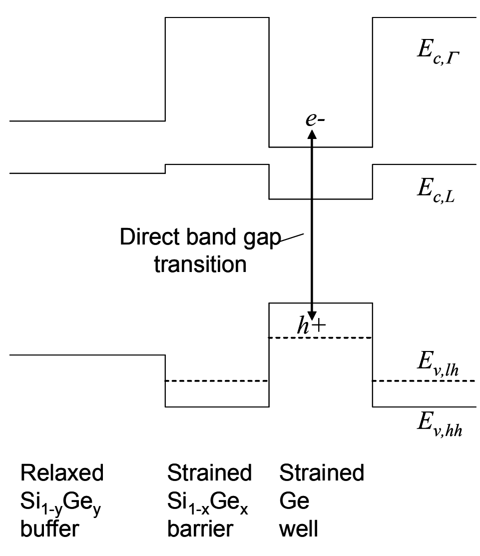

Fig. 2. Band line-up (not to scale). $E_{v,hh}$ and $E_{v,lh}$ are the light and heavy hole band maxima, and $E_{c,\Gamma}$ and $E_{c,L}$ are the conduction band minima at zone center and along the L direction, respectively.

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The room temperature absorption spectra at different reverse bias voltages are shown in Fig. 3. These are calculated from measured photocurrent spectra. Note first that clear quantum confinement is seen in the spectra, with the appearance of strong excitonic peaks at room temperature. The direct absorption edge at low field is shifted to ~ 0.88 eV (compared to ~ 0.8 eV in bulk Ge), by a combination of strain and quantum confinement. The absorption edge shows classic QCSE behavior with field, with a sharp absorption edge shifting to lower photon energies. Exciton peaks are well resolvable even at electric fields as high as $8x10^4$ V/cm. Note that these exciton peaks remain substantially sharper than those typically seen in, e.g., InGaAs/InP quantum wells at similar wavelengths [5].

Treating the quantum well and barrier region as a ~ 0.26 μm thick material with an effective absorption coefficient, the lowest energy exciton has an effective absorption coefficient ~ 6300 cm^{-1} at 0 V. The half-width at half-maximum of this peak is only ~ 8 meV. The absorption edge has a Stark shift from 1408nm to 1456 nm on increasing the reverse bias from zero to 4 V. The maximum change of effective absorption coefficient is 2800 cm^{-1} between zero and 3 V bias, which is comparable to or larger than typical III-V structures at similar wavelengrths [5]. Fig. 4 shows the contrast ratio between the absorption coefficient under bias and zero bias. The bandwidth with contrast ratio higher than 3 is 28 nm, and the peak ratio is 4.69 at 1461 nm.

In conclusion, we have observed quantum confinement and strong QCSE electroabsorption at room temperature at the direct gap in Ge quantum wells with SiGe barriers grown on silicon substrates. Despite the fact that Ge is an indirect gap semiconductor, the electroabsorption performance is comparable to or better than that of III-V quantum wells at similar wavelengths. This is very promising for practical compact low-power, high-speed optical modulators fully compatible with Si CMOS electronic device fabrication.

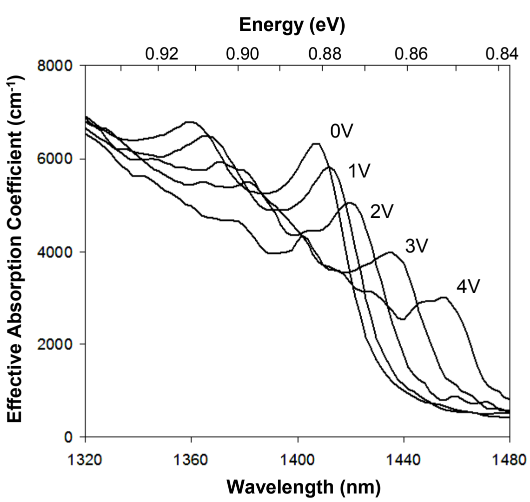

Fig. 3. Spectra of effective absorption coefficient at different reverse bias voltages, as calculated from measured photocurrent spectra.

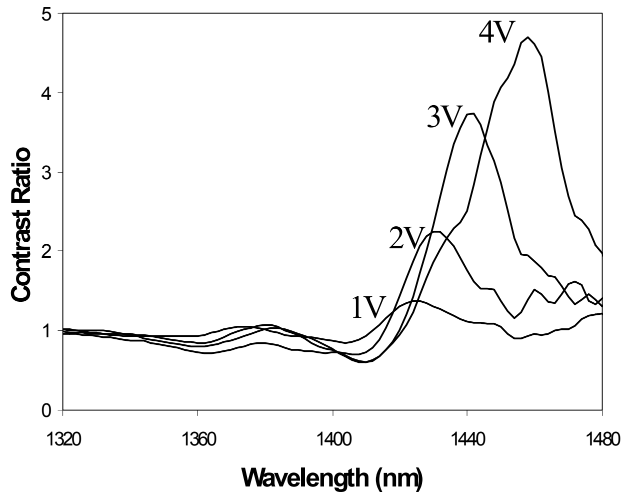

Fig. 4. Contrast ratio of effective absorption coefficients at different bias voltages relative to that at zero bias.

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