Germanium quantum wells for high-performance modulators in silicon photonics

Thin germanium layers on silicon may finally give Group IV optoelectronics the performance of the best III-V devices

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Silicon electronics dominates information processing, and offers a remarkable technology for making very complex systems for very little cost. Many of the waveguide passive optical components that we use today in telecommunications, such as wavelength splitters, use the same technology base – the silicon, silicon dioxide and silicon nitride that are the semiconductors and insulators of electronics become the waveguides of optics. The idea of one platform where could integrate everything – electronics, optics, and optoelectronics – is particularly attractive and could transform the applications of photonics. But silicon technology has a major weakness – it does not have strong optoelectronic effects we can use for emitting or modulating light. The mechanisms in silicon are very weak compared to those we use routinely in optoelectronic devices made from the III-V semiconductors like GaAs, InP, and InGaAs. This weakness makes it difficult to put information onto light beams using silicon structures, either for telecommunications applications, or for emerging applications like dense optical interconnects.

III-V materials are, however, difficult to integrate with silicon for a number of reasons, not the least of which is that the Group III and Group V materials are also the dopants that make silicon conducting. We could turn to other Group IV materials, such as germanium, which is routinely integrated with silicon in modern electronics, but none of those Group IV materials shares the same "direct gap" physics we exploit routinely in III-V optoelectronics (see the sidebar "Direct and indirect gaps").

Despite the absence of any strong microscopic mechanism in silicon, the other attractions of silicon as a platform are compelling; as a result, there has been impressive work using high-Q resonators or long structures to make optical modulators that can exploit the weak effects in silicon (in particular the carrier density dependence of refractive index). Silicon photonics as a research field has shown strong progress [1]. This technology is being commercialized by a number of companies, including Luxtera Corporation, for example, which has succeeding in integrated the silicon photonics technology with silicon electronic integrated circuits. But there is no doubt that we would like to have the much stronger mechanisms of III-V materials to make compact, high-speed, low-power devices. The engineering freedom that strong effects give us would allow us to design devices without high-Q resonators, hence avoiding their associated fabrication challenges, and their precise temperature and tuning requirements.

One of the major approaches used today in telecommunications to impose information onto light beams in III-V structures is the quantum-confined Stark effect (QCSE) [2]. The QCSE is a strong change in optical absorption with voltage that is seen in quantum well structures in direct gap materials. Quantum wells are thin (e.g., 10 nm) layers of one semiconductor with a smaller band gap (e.g., InGaAs) between materials with larger band gaps (e.g., InP). The use of modulators rather than direct modulation of lasers has several advantages, including reduction of "chirp" (undesired sweeping of the wavelength under modulation) and avoidance of limits on the modulation speed of lasers. When we consider integration with electronics, and/or dense arrays of optoelectronic devices, modulators have several further system advantages. In particular, the additional power required to run the laser is not consumed on the chip, reducing on-chip power dissipation, and the laser wavelength, power, and mode structure can be set and controlled away from the hostile environment of the chip, with its high and widely varying temperatures. Especially if the modulator is not a finely tuned resonant structure, precise temperature control is not required on the chip at all. Although it is sometimes presumed that a silicon laser is a necessary breakthrough for usable silicon photonics, in fact a good modulator may actually be more important in practice, and there is no particular need to generate the optical power on the chip. After all, in electronics transistors do not generate electrical power, being merely modulators of electrical power from elsewhere.

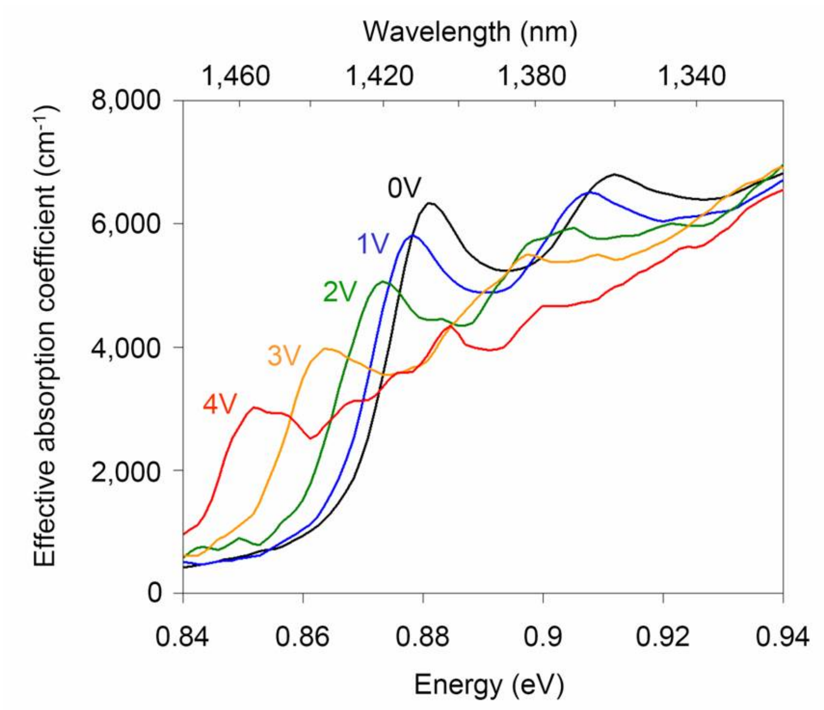


Figure 1. Absorption spectra (from photocurrent) of Ge quantum wells on silicon substrates as a function of reverse bias on the diode structure containing the quantum well layers. [3]

On the face of it, since the Group IV materials like silicon and germanium are indirect, and the QCSE had only been seen in direct gap semiconductors, we still would have no strong modulation mechanism for Group IV materials. Recently, however, we were able to observe the QCSE in germanium quantum wells grown on silicon substrates [3 - 5]. The key point is that we can see this effect at the direct gap of germanium, even though there is a lower indirect gap with some additional weak optical absorption. Typical spectra are shown in Figure 1. Here we see the clear shift of a strong optical absorption edge to lower photon energies (longer wavelengths) that is typical of the QCSE. In a further surprise, these QCSE spectra are at least as clear and strong as good QCSE in III-V materials at similar wavelengths. Finally in a Group IV structure we are able to see optoelectronic modulation physics that is as good as or possibly even better than that in III-V materials. These structures have also been demonstrated to work in the "C-band" telecommunications wavelengths near 1.55 microns, and at the temperatures of operation of high-performance silicon electronic chips (e.g., 90° C) [4].

Very recently we have been able to demonstrate the first optical modulator devices using this approach [5]. As is typical with QCSE modulators, the devices are electrically in the form of reverse biased diodes. Various different forms are possible for QCSE modulators, including waveguides and "surface-normal" devices (i.e., with the light propagating perpendicular to the surface, rather then parallel to it as in a waveguide), and structures both with and without resonators. Since the QCSE in the germanium quantum wells is at least as strong as that in the III-V materials, we expect all of these kinds of structures to be possible. The first working devices have used a novel "side-entry" configuration (Figure 2) that uses a low-Q Fabry-Perot resonator operated at an angle; this particular approach, in contrast to waveguide structures, gives a modulator with a very large misalignment tolerance.

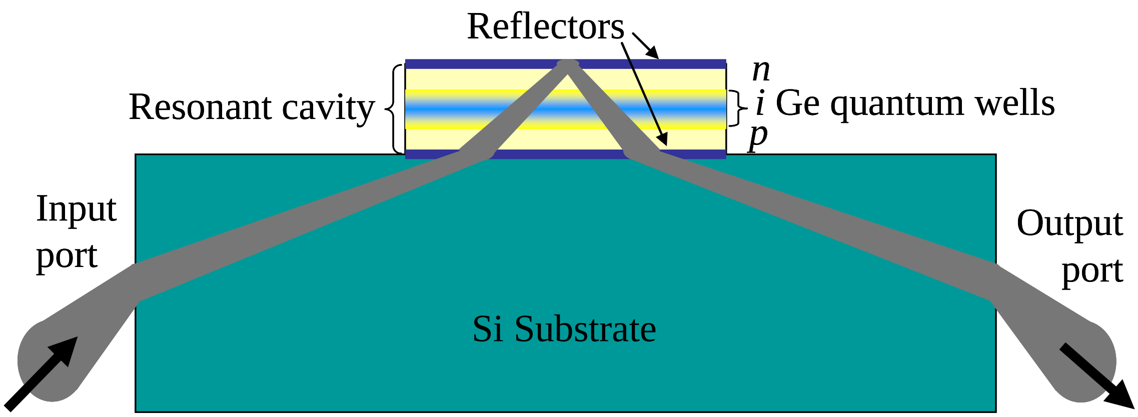


Figure 2. Schematic diagram of the side-entry Ge quantum well modulator (not to scale). The quantum wells are contained within an intrinsic (*i*) region of a *p*-*i*-*n* diode that also forms a low-Q resonator structure. The diode is reverse biased to operate the device.[5]

With this discovery of QCSE electroabsorption in germanium quantum wells grown on silicon, the prospects for a fully functional, high-performance platform for electronics, optics, and optoelectronics, all potentially integrated on one chip, appear to have taken a major step forward. The result may be lower cost, smarter, and higher performance optoelectronics for telecommunications and networks, as well as new generations of dense low-power optoelectronics for computer interconnects [6].

Sidebar

Direct and indirect gaps

The behavior of semiconductor materials is often described in a so-called "band structure", in which the energies of the various possible electron states in the material are plotted as a function of their (effective) momentum $\hbar k$, where $\hbar$ is Planck's constant divided by 2π ($\simeq 1.054\times 10^{-34}$ Joule-seconds) or more commonly, just as a function of the "wavevector" k. On such a diagram, the states group into "bands" that appear as lines (or surfaces); though these appear as continuous lines, they are actually composed of very closely and equally spaced points or states. The most important sets of states for describing semiconductors are the highest "valence" band, in which every state is occupied by an electron in the pure semiconductor, and the lowest "conduction" band, in which every state is correspondingly empty.

In a "direct gap" semiconductor, the lowest point in the conduction band lies directly above the highest point in the valence band. Most of the III-V materials in use for optoelectronics are direct gap semiconductors. Silicon and germanium, which are Group IV materials (from Group IV of the chemical periodic table), are both "indirect gap" semiconductors. In an indirect gap semiconductor, the lowest point in the conduction band is *not* directly above the highest point in the valence band (see Figure A).

It is relatively unimportant whether a semiconductor is indirect or direct for making electronic devices like transistors. But for optoelectronic devices, the difference is crucial. The reason is that the photon, the particle that makes up light, has essentially negligible momentum when viewed on the scale of a semiconductor band diagram.

We can view a simple "direct" optical absorption transition in which a photon is absorbed as taking an electron from the valence band and putting it in the corresponding state directly (or "vertically") above in the conduction band, with the energy separation of the states corresponding to the photon energy $h\nu$, where h is Planck's constant and ν is the frequency of the light. The opposite process, in which an electron falls from the conduction band to an empty state in the valence band essentially directly beneath it, generates a photon, and is the principle light generating mechanism in all semiconductor lasers and most light emitting diodes. Such direct processes are strong, both in absorption and emission. But the corresponding processes for absorption and emission across the indirect gap are much weaker. Such indirect transitions cannot take place only with a photon, because it does not have enough momentum; a "phonon" – the quantum mechanical particle associated with the vibrations of the crystal lattice – is required to complete the transition. Such indirect processes are much weaker, and this weakness is the main reason why indirect semiconductors do not make good light emitters. If we put electrons in the conduction band, they will fall to the lowest energy point in the conduction band; the corresponding "holes" – absences of electrons – in the valence band will rise to the highest point, just like bubbles rising towards the surface of water. In a direct gap semiconductor, these "pools" of carriers (electrons and holes) will be directly above one another, and strong direct optical emission can occur. In an indirect semiconductor, however, only the weaker indirect emission is possible, resulting generally in poor light emitters.

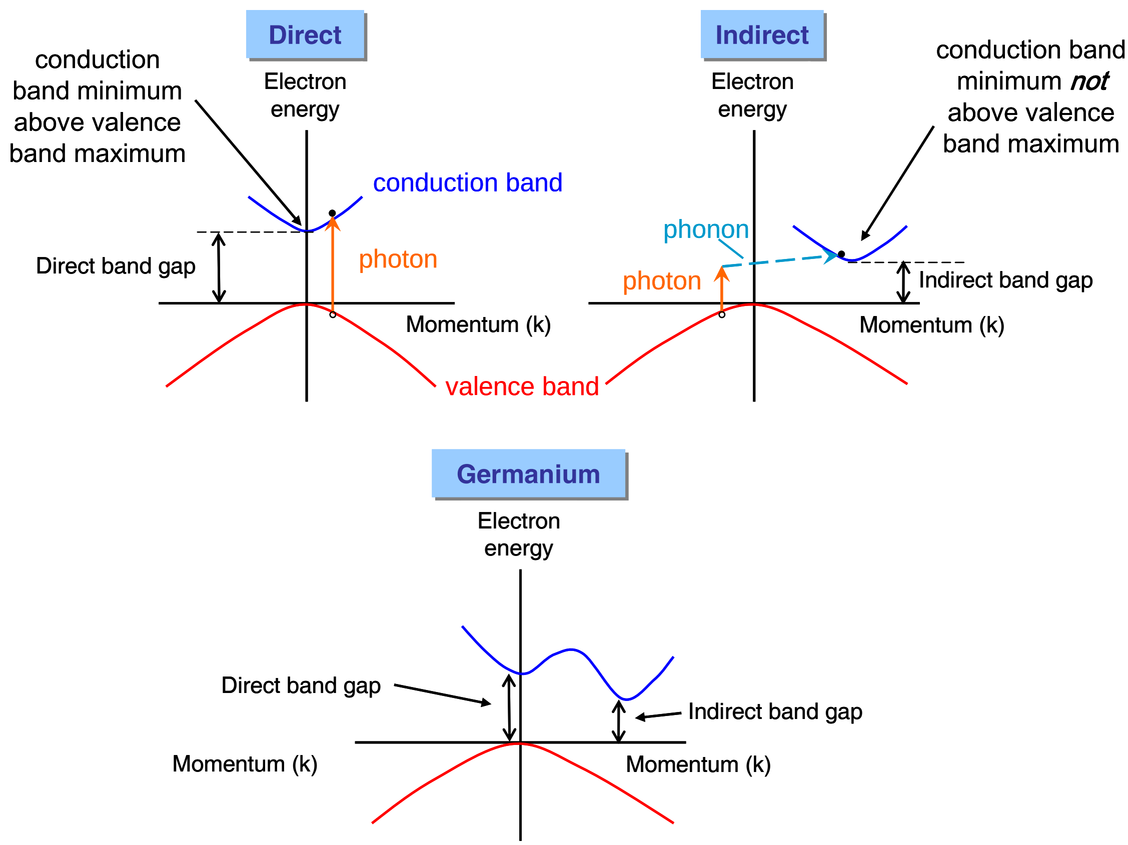
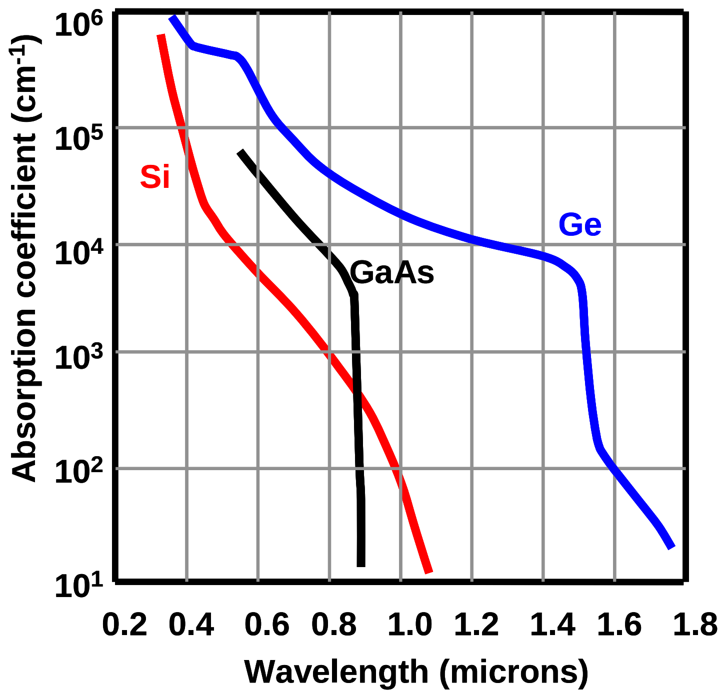


Figure A. Illustration of the band structure of direct and indirect gap semiconductors, and of germanium.

Germanium is an indirect gap semiconductor, but it also has a direct gap at slightly higher photon energy. Though it still does not solve the problem of efficient optical emission, it does show strong, direct optical absorption that rises strongly near 1.5 microns wavelength, with also a weaker indirect optical absorption tail at longer wavelengths (lower photon energies). The direct absorption can be used for photodetectors, and is used here also for modulators in quantum well structures. The physics of the direct absorption in germanium is identical to that in the III-V semiconductors. Figure B shows the resulting optical absorption spectra.



- Figure B. Optical absorption spectra for silicon, gallium arsenide, and germanium. Gallium arsenide shows a strong direct absorption edge at about 0.87 microns. Germanium shows a strong direct absorption edge near 1.55 microns, and a weaker indirect absorption tail extending to longer wavelengths. Silicon shows a weak indirect absorption tail into the infrared wavelengths, and does not show comparably strong absorption until well into the visible spectrum. (After A. Nemecek et al., IEEE J. Sel. Top. Quantum Electron. **12**, 1469-1475 (2006).)

References

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