Si, Si–Ge and the new heterostructure world

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Semiconductor heterostructures based on AlAs/GaAs and other III–V compounds have been the focus of active research for some time now. In the last decade, a new heterostructure material, the strained Si/SiGe system, has emerged. This heterojunction technology can potentially be integrated into the current VLSI environment with large-scale impact in the growing microelectronics market. Si/SiGe heterojunction bipolar transistors with cut-off frequencies exceeding 100 GHz and other electronic and optical devices with superior properties compared to all-Si technology have been demonstrated in laboratories worldwide.

THE microelectronics industry is dominated by silicon MOS and bipolar transistors. These are homojunction devices where carrier flow is controlled spatially by the introduction of suitable dopant atoms. To overcome some of the limitations and design trade-offs involved in these devices, the possibility of using multiple semiconductors was actively pursued in the seventies. These new heterostructure devices utilized two or more different semiconductors grown epitaxially on a common substrate. Because of the different electronic structure and bandgaps, carrier accumulation (or depletion) could be controlled independent of dopant profiles. Furthermore, it was possible to control the potential and electric fields seen by electrons and holes independently. This added flexibility eased some of the constraints in traditional device design and led to rapid developments, in heterojunction bipolar transistors (HBTs) and heterostructure lasers[1]. With the advent of advanced epitaxial growth techniques like molecular beam epitaxy (MBE) and the chemical vapor deposition (CVD), it was possible to control composition and thickness on a monolayer scale. This resulted in a gamut of quantum effect devices based on tunnelling, size quantization and other quantum mechanical effects[2].

Most of heterostructure research till today has been carried out in the AlAs/GaAs material system. These two III–V compound semiconductors are lattice-matched to 0.1% and have similar chemical and structural properties. Epitaxial growth across the hetero-interface is almost perfect with negligible interface states or misfit dislocations. However the dominant semiconductor, silicon, lacked such a chemically similar lattice-matched partner. Although the III–V polar compounds GaP and AlP are reasonably lattice-matched to silicon, they are chemically incompatible. In addition, they act as dopants in the silicon lattice. Initial attempts of growing Si/GaP heterostructures in the late seventies were met with a host of cross-doping, surface segregation and three-dimensional growth problems and were quickly abandoned. Subsequent efforts concentrated on the more chemically similar Si/Ge system. The 4% difference in the lattice constants of Si and Ge, however, was a major stumbling block. This mismatch gave rise to misfit dislocations at the interface and the threading dislocations propagating to the surface through all active layers. The dislocations introduced efficient deep-level traps that reduced carrier lifetimes and increased leakage currents significantly. This problem was overcome in the early eighties with the development of strained layer epitaxy[3], when it was realized that the lattice mismatch can be accommodated by homogeneous strain in sufficiently thin epitaxial layers without the generation of dislocations. Subsequently rapid advances were made in the strained Si/Ge heterostructure technology[4].

Si and Ge are completely miscible and form stable alloys over the entire composition range. The lattice constant of the alloy $Si_{1-x}Ge_x$ can be linearly interpolated between the bulk lattice constants of Si and Ge. Figure 1 illustrates the epitaxial growth of such an alloy on a

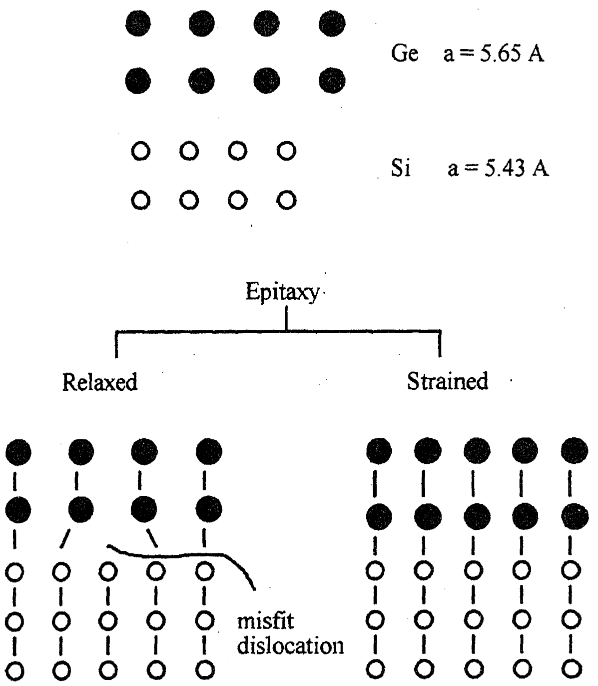

Figure 1. Schematic illustration showing the two different modes of epitaxial growth of a thin film lattice mismatched to the substrate.

lattice mismatched silicon substrate. Initially the lattice constant of the film adjusts to match the substrate. In this case, the film is under compressive strain. Beyond a certain 'critical thickness', the strain energy exceeds the energy to generate a dislocation and the film relaxes. Under metastable conditions, the critical thickness is a function of the mismatch and the growth temperature. It has been calculated theoretically by People *et al.*[5] and also verified experimentally. For a $\mathrm{Si_{0.8}Ge_{0.2}}$ film grown at ~ 600°C, this number is about 1000 Å. Since most heterojunction devices today use active layers with thicknesses well below 1000 Å, the critical thickness poses no major constraint.

The considerable strain in these films profoundly affects the electronic and optical properties. It changes the bandgap, splits conduction and valence band degeneracies and affects the band alignment across the interface. Figure 2 shows the bandgap of a compressively strained $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ alloy compared to the unstrained case as a function of germanium content. For fixed composition, the bandgap is drastically reduced with strain. Thus strained layers with bandgaps spanning the important 1.3–1.55 μm range can be grown with low germanium content and within critical thickness limitations. P-i-N photodetectors fabricated from such structures show considerable promise for fibre optic communications. The strain also modifies the band alignments as shown in Figure 3. Depending on whether the film is under compressive or tensile strain, the alignment can change from weakly type-I with negligible conduction band offset to strongly type-II with substantial offsets in both bands. Thus electron and hole transport can be individually controlled through 'strain' engineering.

The most important device application to date has been the Si/SiGe/Si heterojunction bipolar transistor (HBT). Figure 4 shows the band diagrams of a conventional bipolar junction transistor (BJT) and a HBT. In a BJT, the base current is largely determined by the reverse injection of holes from the base into the emitter. To reduce the base current and obtain high gains, the base doping is typically an order of magnitude less than the emitter doping. The low doping however increases the parasitic resistance of the thin base and substantially degrades maximum operating frequency of the transistor. In an HBT utilizing a strained SiGe alloy as the base, the valence band offset acts as a barrier which prevents hole injection. Thus the base doping can be increased without compromising on gain. This substantially improves the high frequency performance of the device. Very impressive cut-off frequencies exceeding 100 GHz have been achieved in Si/SiGe/Si HBTs[6], far exceeding the best values reported for all-Si bipolar transistors.

Extensive studies have also been carried out in Si/SiGe modulation doped structures. The band diagrams of a typical modulation doped structure are shown in Figure 5. At equilibrium, the mobile electrons are separated from the ionized impurities and are confined close to the interface. The strong confinement results in essentially a two-dimensional carrier system whose properties differ substantially from an equivalent three-dimensional system. The separation from the dopants also reduces coulombic scattering leading to enhanced mobilities especially at low temperatures. Such high mobility two-dimensional systems show novel and exotic physics like the quantum hall effect (QHE) in strong magnetic fields[7]. By using

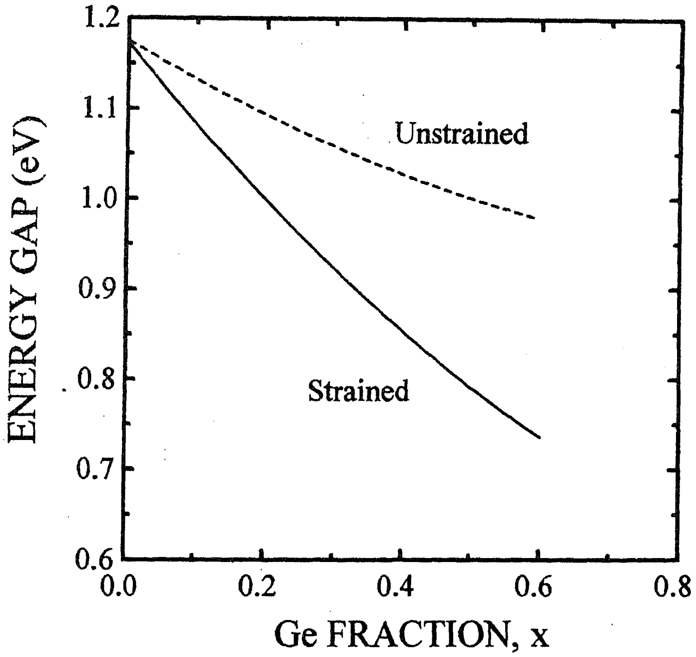

Figure 2. Energy bandgap of a $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ alloy as a function of germanium content for the unstrained and compressively strained cases. The bandgap is drastically reduced by strain.

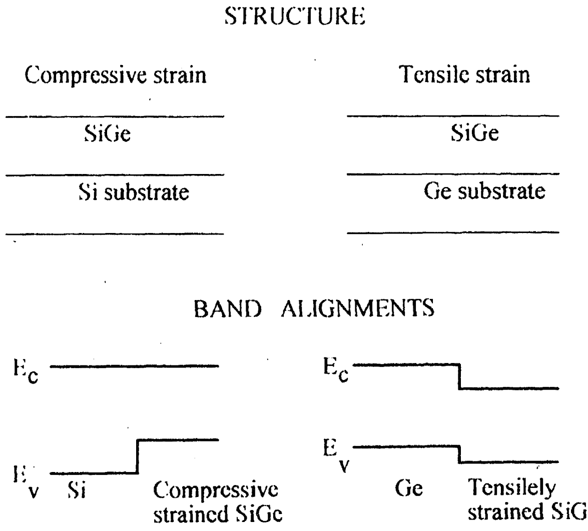

Figure 3. Effect of strain on the band alignment. Depending on whether the film is under compression or tension, the alignment can change from poor type-I with negligible conduction band offset to strong type-II. E_c and E_v denote the conduction and valence bands respectively.

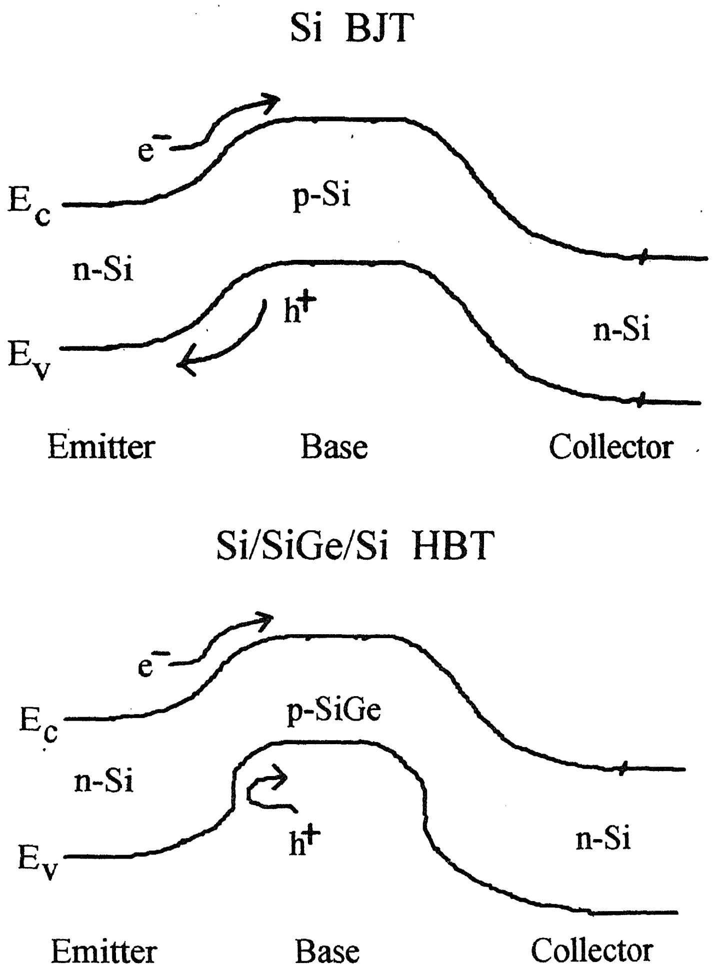

Figure 4. Schematic band diagrams of an all-silicon bipolar transistor and a Si/SiGe/Si HBT. The narrow bandgap base of the HBT results in barriers in the valence band which suppress hole injection into the emitter.

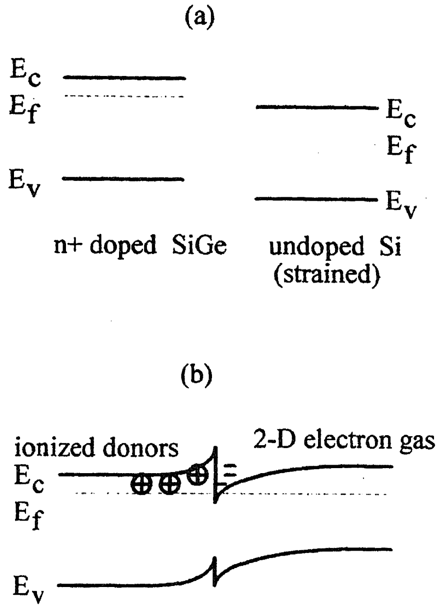

Figure 5. Band diagrams illustrating the effect of modulation doping. The mobile electrons are confined in a narrow potential well at the interface forming a two-dimensional gas which is separated from the ionized impurities leading to high mobilities at low temperatures.

a Schottky gate, the two-dimensional carrier concentration can be changed, thus modulating the current between two contacts. Such a three terminal device behaves like a field effect transistor and is called the high electron mobility transistor (HEMT) or the modulation doped field effect transistor (MODFET). In laboratories in the United States and Japan, HEMTs fabricated from AlGaAs/GaAs heterostructures have exhibited the fastest switching speeds and lowest noise characteristics among all three terminal solid state devices. They are also commercially available today for microwave and high-speed digital applications. Si/SiGe based HEMTs are currently under active investigation[8].

Finally Si/SiGe strained heterostructures have great potential in photonic and optoelectronic applications[9]. Apart from P-i-N photodetectors mentioned earlier, waveguides, modulators and light-emitting diodes have been fabricated. An important device from the military and space point of view is the long-wavelength infrared (LWIR) detector operating in the 8–12 μm range for thermal imaging and night vision applications. Currently, detectors based on a narrow bandgap material like HgCdTe are available. Although these devices have high quantum efficiency, they suffer from material uniformity problems. Si/SiGe heterojunction detectors operating at these wavelengths have lower efficiency, but extremely good pixel-to-pixel uniformity, thanks to the mature silicon processing and integration technology. Large area 400 × 400 pixel imaging cameras using SiGe heterojunction detector elements coupled with Si CCD read-out circuitry have been demonstrated[10]. These results further confirm the suitability of these strained alloys for a variety of applications.

In summary, a relatively new semiconductor heterostructure system based on strained SiGe alloy epitaxially grown on conventional silicon substrates has shown considerable promise for Si-based electronic and photonic device applications. The first commercial products based on this technology, including a 3000-transistor 1-GHz 12-bit DAC from Analog Devices, are expected to reach the marketplace this year[11]. The material also exhibits novel physics due to the strain and complex band structure. Although considerable progress has been achieved, there is enough scope for further research work in this new and exciting field.

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Quantum dots and other mesoscopic systems

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We present a brief description of some of the mesoscopic systems which are of current interest and point out their importance in basic research as well as in tomorrow's technology. We emphasize the need for such research in this country.

Impressive advances in miniaturization

We have recently witnessed a revolution in condensed matter physics. Until recently, this branch of physics has been confined to physical systems that were essentially provided by Nature. However, after quantum wells were first made in the laboratory, it was clear that artificial systems (quantum confined) can be tailored to have unusual and intriguing optical and transport properties. This exciting possibility has now taken a new dimension with the ability to *microfabricate matter* on an unprecedented scale[1]. Utilizing nanofabrication techniques, such as atomically-precise crystal growth and electron beam lithography, it is now possible to literally create any type of structure that one is ingenious enough to conceive, where the *quantum mechanical properties are quite dominant.* Various quantum confined systems, listed below, are well known for their interesting physical properties like:

- Quantum dots (artificial/designer atoms) (zero-dimensional electron systems)—transport, optical and capacitance spectroscopies[1–5],
- Anti-dots (Quantum pinballs) (two-dimensional electron systems)—transport and optical studies[1–2],
- Electron turnstiles (zero-dimensional electron systems)—transport properties[6],
- Quantum rings (one-dimensional electron systems)—observation of the persistent current[2,7],
- Quantum wire superlattices (one-dimensional electron systems)—observation of the collective phenomena[8],
- Semiconductor heterojunctions (two-dimensional electron systems)—observation of the integer and fractional quantum Hall effect (FQHE)[9].

They are created by confining the electron motion in one-, two- and three-dimensions[1–3]. This ability to design new systems is also largely motivated by the eventual application of quantum effects in nanostructures to electronic devices. A commercial application of the two-dimensional electron gas is its use in the high electron mobility transistor (HEMT), which is used in the first stage of satellite receivers. The low noise performance of HEMT at frequencies well above that of other devices has greatly reduced the transmission powers needed. The costs of satellite broadcasting are thereby reduced[10]. It is expected that the quantum confined structures will be widely used in optoelectronics, like in light-emitting diodes and lasers, in fibre-optics communications, optical storage, like the CD players[10]. Other application areas are telecommunications, computers and aerospace. There are also enormous potentials for microlasers[10] in other fields like biology, and even dentistry etc.

Major questions, phenomena

I present below two examples of quantum confined systems which underscore the important message they all convey: basic knowledge as well as potential for applications.

In 1928, Fock[11] studied the problem of a single electron in a parabolic potential and subjected to a perpendicular magnetic field, and after more than sixty years, inter-electron interactions were introduced to that problem[4]. Finally, in 1993, Ashoori *et al.*[5] reported single-electron capacitance spectroscopy in a single quantum dot. Here, electrons tunnel into the dot and change