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Applications of $Si_{1-x}Ge_x$ Strained Layer Alloys for Silicon-based Optical Interconnects

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Abstract

In this paper various components and physics for silicon-based optoelectronic interconnects are demonstrated. These include $Si_{1-x}Ge_x$/Si epitaxial waveguides, a vertical Fabry Perot optical modulator, and the first well-resolved band edge photoluminescence in $Si_{1-x}Ge_x$ strained layers.

Introduction

The speed of silicon VLSI systems is increasingly being limited by inter-chip and inter-board communication rather than by pure device speed. This problem is expected to become more severe in the future since chip I/O demands are expected to grow with increasing integration levels and operating speed, but electrical transmission lines are limited by capacitative and inductive effects to relatively low bandwidth-distance products. It is well known that this electrical "pin-out problem" can in principle be remedied by optical interconnects, as the capacity of a single optical waveguide or optical fiber is several orders of magnitude higher than that of an electrical transmission line.

Attempts to integrate optical interconnects with VLSI circuits to date have faced a basic materials challenge. VLSI electronics is, and will continue to be, based on silicon electronics, whereas optoelectronic components to date are made in III-V materials. This is a problem for two reasons: first, the difficulty of growing polar III-V's on elemental semiconductor substrates, and second, the general incompatibility of III-V materials with standard silicon process technology. In this paper we describe work on basic silicon-based components and materials (silicon and/or silicon-germanium strained layer alloys) for the integration of optoelectronic interconnects onto silicon substrates.

The advent of the silicon-germanium strained layer material system allows one to integrate new functionality onto a silicon substrate. These alloys provide the ability to adjust the bandgap over the range of 1.12 to ~ 0.7 eV without the misfit dislocations which could lead to deep level defects and degrade device performance. For optoelectronic integration, several components and structures are required. If an edge-coupled approach is used waveguides will be required to transmit optical signals from the edge of the chip to their desired on-chip location. Second, a receiver for converting optical signals to electrical signals is needed. Finally, for data transmission, optical modulators or emitters are required.

Previous work has clearly demonstrated how $Si_{1-x}Ge_x$ strained layers may be used for high-speed detectors at 1.3 μm (impulse response time = 300 ps) [1]. This work will therefore focus on the outstanding elements: SiGe waveguides, a vertical Fabry Perot optical modulator, and the physical basis for light emission from $Si_{1-x}Ge_x$ strained alloys. The first clear evidence of optical emission from a band edge transition is shown.

Experimental Results:

Epitaxial waveguides

Waveguides are a basic component used to interconnect optoelectronic components, and they form the backbone of devices such as splitters and directional couplers. Waveguides can in principle be made by creating a high index of refraction layers on a low index substrate. Such confinement has previously been demonstrated in silicon using lightly doped epitaxial layers on top of heavily doped substrates [2]. The requirement of heavily-doped substrates, or at least heavily doped buried layers, (to lower the refractive index) makes integration of such waveguides with conventional IC's difficult. Alternatively, silicon-germanium alloys can be used as the confining layer (on normal substrates) since SiGe has an index of refraction greater than that of silicon. One can estimate an index of refraction of 3.52 at 1.3 μm for $Si_{0.99}Ge_{0.01}$ (vs. 3.50 for Si). The presence of 1% Ge does not impose any substantial critical thickness limitations due to strain. An experimental rib waveguide has been made by epitaxial growth of 2 μm of $Si_{0.99}Ge_{0.01}$ followed by plasma etching (fig. 1) of 8 μm stripes. Waveguiding has been observed using lensed fibers and butt coupling. The mode pattern has not yet been resolved, however. Similar structures with low loss have been fabricated by Soref et al [3].

Si-doped single mode waveguides have also been demonstrated in doped SiO_2 layers on silicon [4]. However, because of the small index grading available, a 20 μm buffer oxide layer and a guiding layer of 8 μm is required. Therefore such structures would be very difficult to integrate with VLSI circuits. Alternatively, our structures could easily be integrated into I.C.'s by etching a trench and selectively filling it with $Si_{1-x}Ge_x$ to create a planar structure before the beginning of device processing.

Silicon modulators

To transmit data off-chip, on-chip modulators or emitters are required. In this section, the results of on-chip silicon intensity modulator at 1.3 μm are described. Since free carriers lower the index of refraction of semiconductors, one can modulate the phase of light in silicon by free carrier injection. To convert this phase modulation to intensity modulation, we have placed a silicon p-i-n diode inside a vertical Fabry-Perot cavity (fig. 2). The lower mirror is made by a buried oxide ($\sim$ 2200 Å) formed by oxygen implantation and annealing. The epitaxial n^+–i–p^+ silicon is $\sim$ 7 μm thick, and the upper mirror is polysilicon (1000 Å) on oxide (2200 Å) to give a calculated finesse of 7 and reflectance vs. Δn (at 1.3 μm). If one is operating near the point of maximum sensitivity, an index change of 4 x 10^{-3}, corresponding to an estimated carrier density of

$2x10^{18}cm^{-3}$, would yield $\sim$ 25% modulation depth. Coupling to an external single mode fiber is performed by simply putting a cleaved fiber against the device. An external laser supplies the light, and the reflected signal is separated from the incoming signal by a directional coupler.

Experimental results in fig. 3 show the results of a 60 μm x 60 μm device operating at a NRZ bit rate of 50 Mbits/s. With a current density of $6x10^3$ A/cm^2 the modulation depth was 10%, and that the received signal follows the transmitted signal (with a delay of 70 ns due to the driving electronics) is clearly evident [5]. Higher frequency measurements showed a -3 dB frequency of 40 MHz. Because of the F-P resonance, this structure operates at $\sim$ 1/10 the current density of an earlier Si p-n device [6]. By scaling the size of the device to match that of the fiber core ($\sim$ 8 μm diameter), the operating current of the device would be $\sim$ 3 mA. 40 MHz may be adequate for the fiber-to-home return link, but it is not acceptable for VLSI interconnect applications. Higher speed free carrier devices may be possible in a Si/SiGe/Si HBT structure where high carrier densities and rapid switching times could be obtained.

Silicon-germanium strained layer photoluminescence

An alternative to on-chip modulation of an off-chip light source is to generate the optical signal on-chip. It has been proposed that various short period strained Si/Ge superlattices will have a direct bandgap since the conduction band minima at X would be "zone-folded" back to the Γ-point by the long range periodicity [7,8]. All experiments to date, however, have yet to show any well resolved electronic transitions in strained SiGe structures from the band edges. Some reports of PL are almost certainly due to dislocations [9] and others give rise to a very broad signal of uncertain origin [10,11,12].

In recent experiments in longer period superlattices (period $\geq$ 45 Å) grown by rapid thermal processing, the first clear band-edge photoluminescence from strained silicon-germanium alloys was observed. The PL signals of a two $Si_{0.82}Ge_{0.18}$/Si superlattices (489, 50 45-Å periods; 416, 10 80-Å periods) grown by RTCVD are shown in fig. 4 [13]. At 2K, the luminescence is due to bound excitons. A clear no-phonon line, as well as phonon replicas are observed, and TO phonon consists of 3 local modes: Si-Si, Si-Ge, and Ge-Ge. At temperatures over 20 K the PL is due to free excitons, with a similar no-phonon line and phonon replica. Free exciton PL in silicon always requires a phonon because of the indirect nature of the bandgap. Since $Si_{1-x}Ge_x$ films are random alloys, however, the usual Bloch states are no longer exact eigenstates, and mixing between the Bloch states by the alloy scattering allows no-phonon optical processes to occur in what is an indirect gap semiconductor. Although the spectra shown are from superlattices, the PL is not related to the superlattices except for quantum confinement increases in the transition energies. Similar spectra have also been observed in single strained layers. Future work will involve measuring the oscillator strength of the no-phonon transition, and performing short period ($\sim$ 10 Å) superlattice experiments.

Summary

In summary, silicon-based optoelectronic components may be a viable approach for optical interconnects for ULSI circuits. This paper has demonstrated epitaxial SiGe waveguides, a Fabry Perot vertical free carrier modulator, and the first clear evidence of light emission from band-edge transitions in $Si_{1-x}Ge_x$ strained layer alloys. No-phonon free-exciton photoluminescence has been observed in excess of 200 K.

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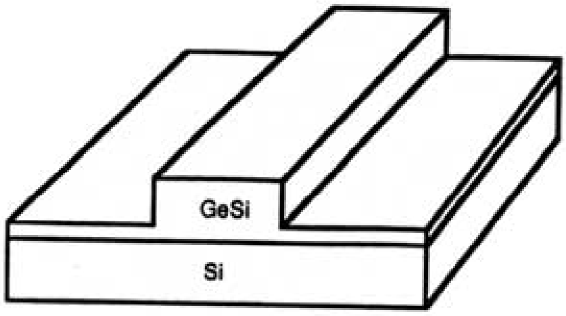

Fig. 1: Cross section of $Si_{1-x}Ge_x$ rib waveguide structure.

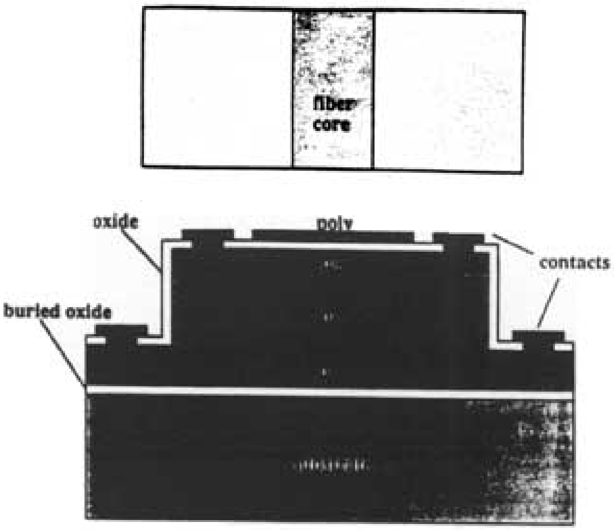

Fig. 2: Cross-section of p-i-n Fabry-Perot optical modulator at 1.3 μm. Note the buried oxide mirror and the butt-coupled single mode fiber.

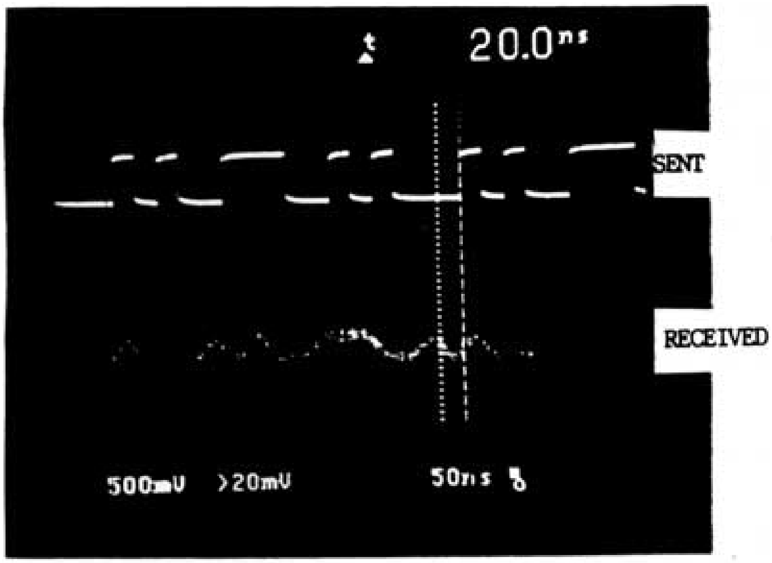

Fig. 3: Encoded data (NRZ) and received signal in a 50 MHz transmission experiment.

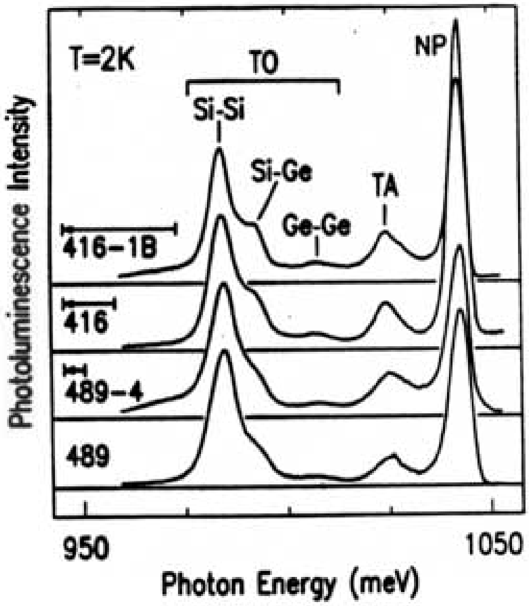

Fig. 4: Bound exciton photoluminescence of two $Si_{0.82}Ge_{0.18}$/Si superlattices. Note the no-phonon signal and phonon replicas.