switching speed).[2] To date, developments in high speed Si logic gates have resulted in switching speeds exceeding 1Gbit/s. At this rate, the synchronization of clock and data distribution becomes a formidable problem, and electrical interconnects have been pushed to their limit.

Optoelectronics offers new solutions to the problem. The fiber medium is a very low loss, low dispersion transmission channel, and over a short distance (usually less than a few meters in a computer) is virtually unlimited in bandwidth. The guiding of light also eliminates yet another serious problem: crosstalk.

The two key experiments are 1) high speed modulation of GaAs-on-Si lasers and 2) high speed GaAs-on-Si photodetector. High speed modulation was demonstrated since GaAs/AlGaAs lasers must be modulated at Gbit rates for off chip communications by the microwave signals generated on a chip. At the receiving end, a high speed photodetector converts fast optical pulses to microwave signals, and for this reason, GaAs-on-Si p-i-n photodetectors were also studied in detail.

Although Si ($\lambda_{gap} \sim$ 1.1 μm) absorbs GaAs laser emission ($\lambda \sim 0.85$ μ), it suffers from low sensitivity when high speed is of paramount importance as a result of its large absorption depth ($\sim$ 10 μm for Si versus $\sim$ 1 μm for GaAs). For a given quantum efficiency, GaAs requires only one-tenth of the transit region as compared to Si, thus reducing the transit time by 10 times. For a given transit time, GaAs is obviously more sensitive due to efficient absorption.

The high speed microwave current modulation of a GaAs-on-Si laser was demonstrated at frequencies as high as 4.5 GHz (3dB bandwidth is 2.5 GHz).[3] The laser used in the modulation experiment is one with a stripe geometry (10 μm wide, 400 μm long) with a gain guided waveguide commonly known as a ridge-waveguide. It has a minimum threshold current of 40mÅ, an external quantum efficiency of 85%, and a lasing wavelength of 8600Å. The laser is mounted into a microwave package, and dc bias and high frequency modulation signals are applied through a microwave bias-T. The frequency response was measured by detection with a high speed commercial p-i-n photodiode.

Despite all the difficulties with GaAs-on-Si laser growth, the frequency bandwidth (2.5 GHz) rivals that of a typical GaAs-on-GaAs laser (3 dB bandwidth 2 GHz) with the same gain guided ridge waveguide structure.[4] Further increase in modulation frequency (as high as 20 GHz) is expected with index guided stripe structures, better fabrication techniques, and reduced size.

The detector structure used is a conventional p-i-n diode with the intrinsic region width designed to give a transit time comparable to the RC time constant to balance the two limitations. The detectors show normal GaAs I-V characteristics under forward and reverse bias. The detector was illuminated with 5ps optical pulses, and the output of the detector was then measured both with a sampling oscilloscope and a spectrum analyzer. For a 70 × 100 μm^2 area, 2 μm intrinsic region GaAs-on-Si detector, the impulse response shows a 45 ps FWHM, corresponding to a 3dB bandwidth of 4GHz.[5] This compares very well with the results obtained with identical GaAs-on-GaAs p-i-n detectors fabricated using the same process. Higher bandwidth is expected with the reduction of the detector dimensions.

The combination of laser and detector can provide a working optical chip to chip (or board to board) interconnect at 1Gbit/s rate, which can find applications already in existing computer systems.

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LARGE AREA EPITAXIAL GAAS AND AL$_x$GA$_{1-x}$AS FILMS ON ARBITRARY SUBSTRATES

E. YABLONOVITCH
BELL COMMUNICATIONS RESEARCH
NAVESINK RESEARCH CENTER
RED BANK, N.J.

Thin-film semiconductors have always represented a tradeoff between material quality and ease of preparation. Photonic devices require the highest quality epitaxial films, in which the atoms are in exact registry with an underlying crystal. But they must be grown on, and are accompanied by, cumbersome and expensive bulk single crystal wafer substrates.

The apparent inevitability of the compromise has given a role to lesser quality films such as amorphous Si and GaAs on Si. For some time now, researchers have sought to avoid that compromise altogether by attempting to create epitaxial quality thin films on arbitrary substrates while simultaneously maintaining the ultimate in crystalline perfection. If such a materials technology were available, it could be expected to play an increasing role in semiconductor and opto-electronics.

The ability to prepare such films leads to a number of interesting possibilities. An obvious one is to combine GaAs optoelectronic and Si integrated-circuit technologies by mounting lifted-off AlGaAs lasers and detectors on Si chips, with the AlGaAs devices providing secure, high-speed interchip communications by optical means. More exotic possibilities, such as mounting GaAs lasers between metal plates to increase thermal dissipation and to reduce noise by suppression of spontaneous modes, can also be envisioned.

One approach is to regard the substrate wafer as a kind of reusable template that can be separated physically from the film after epitaxial growth is completed. The key is to incorporate a release layer in the structure that allows separation to occur. In very early work,[2] Milnes and Feucht proposed that an epitaxial Si film could be separated from an Si substrate by melting an intermediate release layer of Si_xGe_{1-x} alloy. Later the so-called "CLEFT" approach developed by Fan[1] achieved separation by means of a striped carbon film deposited on a semiconductor substrate. Upon cleavage, the film separates in the carbon striped layer that is mechanically weaker than the rest of the crystal.

The natural chemical selectivity among different alloys of the series $Al_xGa_{1-x}As$ suggests a simpler approach. In a little noticed paper almost 10 years ago,[3] Konagai et al. showed that good selectivity could be obtained by etching away a release layer of AlAs in hydrofluoric[4] acid. They did not follow up this work, but further improvements were later achieved at Rockwell and described in an unpublished report.[5]

Recently, Yablonovitch, Gmitter, and co-workers at Bellcore appear to have ironed out the remaining kinks in the process. Large-area (cm square), electronic grade, multilayer GaAs and $Al_xGa_{1-x}As$ ($x \leq 0.4$) single-crystal films already containing fabricated devices are lifted off single-crystal GaAs substrates.[6] The substrates can be reused and the films can be mounted on arbitrary substrates, including Si wafers. As a demonstration, these workers fabricated AlGaAs lasers on glass substrates, with no loss of performance.

To achieve these capabilities, two new insights had to be implemented. First, the selectivity had to be made extremely high. This was accomplished by chilling the acid bath below 0°C. Al-rich AlGaAs alloys etch rapidly and independently of temperature, while Ga-rich AlGaAs alloys etch via a thermally activated process. At 0°C, the selectivity between the AlAs release layer and alloys like $Al_{0.4}Ga_{0.6}As$ reaches $\sim 10^7$.

Second, the gaseous reaction products of the etch had to be removed without creating bubbles that could fracture the thin film. This problem was well known,[1] but the intuitively obvious approach of making the release layer as thick as possible to provide a wide opening for the gas to escape is in fact wrong, as wider release layers merely generate more gas. The key is to make the AlAs layer as thin as possible while controlling the stress in the film by a polymeric support layer so that it curls slightly upward as it lifts off. AlAs under layers as thin as 20Å have been used to obtain cm-square $Al_xGa_{1-x}As$ films.

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INTEGRATED OPTICS

COMPACT, LOW-LOSS SEMICONDUCTOR WAVEGUIDE BENDS

R.J. DERI
BELL COMMUNICATIONS RESEARCH
RED BANK, N.J.

Monolithic opto-electronic integrated circuits, integrating active and passive optical and electronic components on a single chip are the subject of active research at numerous laboratories around the world, particularly for potential applications in optical communications systems.

One of the many technical challenges in this field is the fabrication of effective optical waveguide structures using