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Invited

Integration of Optical and Electronic Devices by Impurity Induced Layer Disordering

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In this talk, we review the use of impurity induced layer disordering to monolithically integrate heterojunction bipolar transistors with buried heterostructure lasers and explore some directions in which this technology may develop in the future.

Impurity induced layer disordering (IILD) is emerging as an enabling technology for the planar integration of optical and electronic devices in III-V semiconductors. Layer disordering, or intermixing, is possible because the interface between different III-V alloys is unstable against solid state interdiffusion of the column III elements in the presence of a high concentration of impurity atoms. Thus it is possible under appropriate conditions to induce thin layers of different III-V materials to intermix without melting to produce a uniform layer whose composition is an average of the initial layers.[1] Since this "layer disordering" can be laterally patterned on a wafer, the process enables lateral bandgap engineering by using only impurity diffusions, thereby avoiding damage and contamination commonly encountered in etch and regrowth processes. Lateral interfaces produced with this process are very abrupt and reproducibly controlled. One especially important attribute of IILD is that it enables both optical and electronic devices to be built on the same layer structure within a single set of processing steps.[2]

Impurity-induced layer disordering has been demonstrated with many elements in several different III-V materials. Applications of the technology are most advanced in the GaAs/AlGaAs system where lattice matching is not affected by exchanging Al and Ga atoms. Recent work[3] with InGaAs/InAlAs holds promise of extending applications into a material system capable of lasing operation at wavelengths of 1.3 µm or longer. Although impurities such as zinc, germanium, and selenium have been used silicon has emerged as the preferred impurity in GaAs/AlGaAs because its diffusion is controllable and reproducible while its disordering threshold is considerably more abrupt than zinc. In GaAs/AlGaAs structures, layer mixing occurs at a threshold of about 1.5×10^{18} /cm^3 [4] over a transition region of 25 to 30 nm.[5] One limitation of Si is that it is normally only an n-type dopant for IILD. Since Zn diffuses rapidly and tends to have a shallow diffusion front, a p-type dopant that is as controllable as Si remains to be demonstrated.

IILD has been applied very succesfully to the formation of low-threshold diode lasers. Narrow (3 µm) buried heterostructure lasers made with Si-induced layer disordering exhibited[6,7] cw thresholds as low as 3 mA. The lowest threshold (1.5 mA) achieved without reflectively coating the laser facets was also obtained[7] with Si IILD. The structure introduced by Thornton, et al.[6] for BH lasers made with Si IILD is shown in Figure 1. Lasers with this structure are defined by depositing Si in openings in a Si_3N_4 mask. Lasers (3 µm width) fabricated with a 95% reflecting coating on their rear facets have exhibited an overall conversion efficiency of 40% at 25 mW of single-ended output power. Degradation rates obtained[8] with research prototypes of this laser have operated continuously over 2000 hours at 50°C suggesting that more than 25000 hours is required to reach twice the initial operating current at 10 mW. With an activation energy of 0.7 eV as commonly measured for similar materials, a lifetime in excess of 10^5 hours can be expected.[8] Recently BH lasers of reasonable threshold (8mA cw) have been fabricated[9] by IILD using difusion from a Ge vapor source.

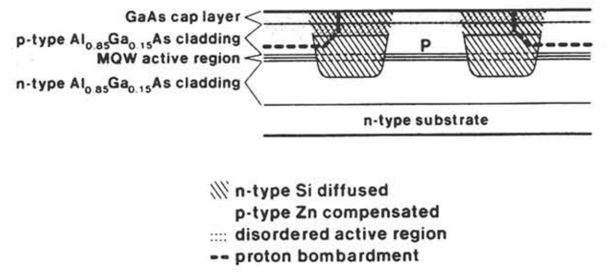

Figure 1. Schematic diagram of a GaAs/AlGaAs buried heterostructure laser fabricated with silicon-induced layer disordering.

Lateral heterojunction bipolar transistors (HBT) with excellent characteristics have been fabricated in GaAs/AlGaAs[10] with IILD. Figure 2 schematically shows the cross-sectional structure of this device. The layer disordering is used to selectively convert the p-type GaAs base into n-type AlGaAs regions that serve as the wide-bandgap emitter and collector for the transistor. Multiple quantum wells of GaAs defined by barrier layers of $Al_{0.2}Ga_{0.8}As$ have been used to increase the transistor gain and maximum device current. High gain transistors are fabricated in an annular ring geometry in order to avoid edge effects by completely surrounding the base with emitter and collector regions. A current gain in excess of 600 has been achieved[11] at 2 mA of collector current with a base width of 0.3 µm. Improved collector and emitter contacts enabled a similar structure to provide up to 45 mA of current from a base area of 10 μm^2 as shown in Figure 3.[11]

An important advantage of integrating optical and electronic devices with impurity induced layer disordering is that the layer structure used in the transistor element is identical to that used to fabricate a low threshold laser element. In fact, forward biasing both p-n junctions in the lateral transistor produces lasing operation in the narrow base region. Threshold currents as low as 6 mA have been achieved[2] in this way with a base width of 1.4 µm. This compatibility of layer structure and processing has enabled[12] the first successful operation of a transistor controlled laser monolithically fabricated with a planar process. The effective threshold current for the transistor controlled laser was 30 µA while the effective slope efficiency was the extraordinarily high level of 100 mW/mA of cw base current.

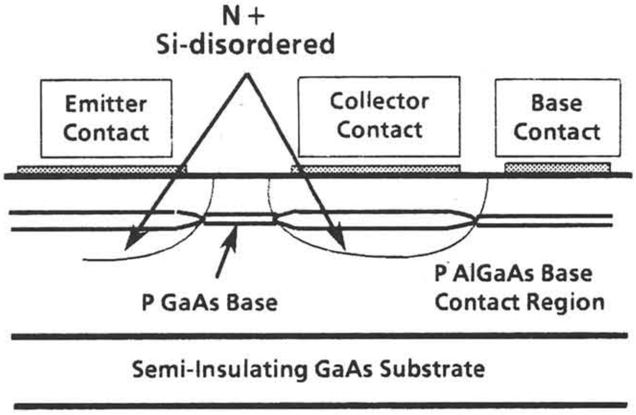

Figure 2. Schematic diagram of a lateral heterojunction bipolar transistor fabricated with silicon-induced layer disordering in a GaAs/AlGaAs heterostructure.

Although the utility of using IILD to integrate optical and electronic devices has been amply demonstrated for GaAs/AlGaAs, IILD is still in an early stage of development as a semiconductor processing technology. The first integrated structures with high performance have been demonstrated[12] in AlGaAs and elementary optoelectronic circuits have been proposed.[13] In the future, it is likely that this technology will be extended to long-wavelength materials such as InGaAs/InAlAs. More sophisticated methods of pattern definition will certainly produce smaller structures than presently attainable. Quantum wire structures made with IILD have already been reported.[14] Reduced device size will likely mean shallow structures for surface-initiated diffusion or the utilization of buried diffusion sources. Laser-assisted desorption during epitaxial growth[15] has already been used to achieve patterned layer disordering from a buried layer of Si. Today, IILD is a viable technique for fabricating high quality optoelectronic devices in AlGaAs. Tomorrow it may enable a new generation of three-dimensional optoelectronic integrated circuits.

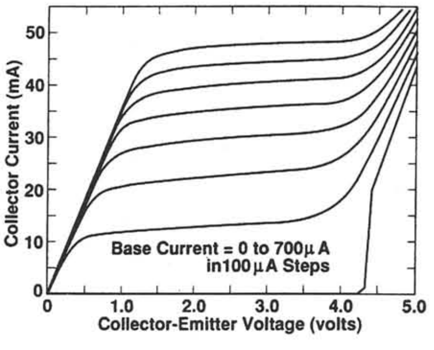

Figure 3. Transistor characteristics in the high current regime for a GaAs/AlGaAs lateral heterojunction bipolar transistor fabricated with silicon-induced layer disordering.

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