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The effects of a variety of different treatments on the diffusion lengths in GaAs wafers ~~have been~~ investigated. Sealed ampule proximity-capped anneals of 16 hours at 950°C were found to increase minority carrier (hole) diffusion lengths in 1×10^{17} Si doped GaAs from initial values of about 0.8 µm to 1.9 µm. This improvement appears to be associated with the reduction in density of a hole trap at E_v+0.3 eV which has a capture cross-section in the 10^{-14}-10^{-15}cm^2 range. The proximity anneal also greatly reduced the densities of electron traps, including EL2, but there was no direct correlation of electron trap density and improved carrier lifetime.

In other studies the effects of isoelectronic In and Sb doping on the hole traps in Be-doped p-GaAs and electron traps in Si-doped n-GaAs (100) grown by molecular beam epitaxy (MBE) have been investigated. The addition of 0.2 to 1% indium causes large reductions of electron trap densities in layers grown at 550°C and also reduces certain hole traps. Homojunction GaAs bipolar transistors npn and pnp have been fabricated with base layers containing In isoelectronic doping and are found to have significantly better characteristics than if the In is omitted.

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DEFECT CONTROL AND DENUDED TRAP ZONES IN THE III-V SEMICONDUCTORS

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1. Statement of the Problem

GaAs is a semiconductor that has a much higher electron mobility than Si. It is essential to a range of high speed integrated circuits that operate at very high clock rates and in the analog microwave region 1 to 30 GHz, or even higher, for radar and detector applications. In addition GaAs is a direct energy gap semiconductor unlike silicon and is the basis of various light emitting devices (LEDs) and heterojunction lasers. Solar cell structures involving GaAs are suitable for high sun concentrations and have higher efficiency than Si cells and greater resistance to degeneration in the space environment. GaAs grown by traditional methods for ingot slices exhibits many native defects and complexes of defects such as gallium or arsenic precipitates, vacancies, interstitials, anti-site defects and dislocations. These cause severe problems in the fabrication of discrete devices or integrated circuits with satisfactory yield and acceptable deviation of device parameters.

The thrust of the work under this grant was to uncover, and when found, study the underlying science of methods of treating GaAs slices, or epitaxial layers grown on GaAs slices, to reduce or getter harmful defects (creating denuded zones) and thereby increase uniformity of the material in a way relevant to device fabrication for high yield and uniform performance.

2. Summary of the Most Important Research Findings

2.1. Introduction

CMU has conducted systematic studies of defect concentrations and diffusion lengths in bulk GaAs in order to identify the carrier-lifetime-limiting defects in n-type GaAs and determine means by which the concentration of these might be reduced. Models commonly used to express carrier trapping and recombination action by point defects in terms of capture cross section and capture kinetics have been considered and developed. These considerations underscore the importance of including minority trap characterization in any comprehensive study aimed at identification of important lifetime controlling centers in any material: a study of majority carrier traps in both n- and p-type material is not equivalent.

The problem of minority carrier injection by electrical means to characterize minority carrier traps with DLTS was then considered. It was found that DLTS measurements may systematically underestimate the concentrations of minority carrier traps which act as recombination centers if these have majority carrier capture cross sections of magnitude comparable to their minority carrier capture cross sections. Relative concentrations of any given trap as varying between specimens can nevertheless be accurately determined if current density during the carrier-injecting electrical pulse is kept constant. Such considerations also suggest that certain combinations of temperature-varying electron and hole capture cross sections may result in strong variations of DLTS peak height with rate window and this has been observed experimentally.

2.2. Improvement of Minority Carrier Diffusion Lengths in GaAs Slices

The effects of a variety of different treatments on the diffusion lengths in GaAs wafers have been investigated. The treatments applied included sealed ampoule anneals in the temperature range 600 to 900°C for times of between 10 minutes and 90 hours on specimens provided with a variety of capping layers. Rapid thermal and sealed ampoule proximity anneals were also carried out, with and without, prior reverse surface damage. The effect of exposure to a hydrogen plasma was also examined. The treatment selected for in-depth study as the most promising was the proximity anneal, without reverse surface damage. Short anneals of 25 to 50 seconds in the chosen temperature range (900 to 1050°C) were found to result in large changes in the electron trap structure to a depth of at least 10 μm from the wafer surface. The 1000°C 16 minute anneal reduced all electron traps except EL2 by at least an order of magnitude to below the detection limits of the apparatus (about 2×10^{13} cm^{-3} for the 1×10^{17} cm^{-3} Si doped specimens) but resulted in only a 50% improvement in diffusion length. No obvious correlation between EL2 concentration and diffusion lengths was found. From these results, we conclude that the defects which manifest themselves as electron traps are not those which limit diffusion lengths in n-material with diffusion lengths of the order of 1 μm.

Hole traps in n-type material, were then studied. A trap labelled HCX was found to be present in all the bulk, n-type specimens examined, whereas two other traps HCW and HCY only appeared in some specimens.

High temperature anneals change HCX and HCY concentrations by amounts roughly comparable to what might be expected from the observed changes in diffusion length. Increases in diffusion length from an initial value of 0.8 μm before anneal to between 1.7 and 1.9 μm after anneal were found. Preliminary measurements of the activation energy and capture cross section show HCX at about E_v + 0.3 eV with a hole capture cross section in the 10^{-14}-$10^{-15}cm^2$ range. Its concentration in material of diffusion length of about 1µm is in the $10^{15}cm^{-3}$ range. HCX apparently plays an important role in controlling the minority carrier lifetimes in bulk material. The emission line for HCX lies in a position somewhat close to that reported for HL6 and HL11 in earlier studies and is believed to be a native defect complex and not a simple impurity defect level.

2.3. Improvement of MBE Grown Layers In Epitaxial Layer Studies

The effects of isoelectronic In and Sb doping on the hole traps in Be-doped p-GaAs and electron traps in Si-doped n-GaAs (100) grown by molecular beam epitaxy (MBE) have been investigated. The dominant hole traps in our Be doped layers are at about E_v + 0.56 eV (H4) and may be the HL8 trap (0.52-0.54 eV) reported previously and at E_v + 0.29 eV (H2). The concentrations of H4 and H2 are reduced by three orders of magnitude (from $10^{15}cm^{-3}$ for H4, $10^{14}cm^{-3}$ for H2) by increasing the growth temperature from 500 to 600°C. Photocapacitance measurements support the view that this trap is As_{Ga}^{++} and not a trap associated with Fe_{Ga}. Additions of 0.2% to 2% In or Sb for growths at 500 or 550°C have no affect on the concentration of this anti-site defect trap but cause a considerable reduction of the trap at 0.29 eV (H2). The two dominant electron traps M3 (E_c-0.33 eV) and M6 (E_c-0.62 eV) in our n-GaAs layers are drastically reduced in concentration by up to three orders of magnitude by introducing 0.2-1 at % In or Sb and increasing growth temperature from 500 to 600°C. In and Sb appear to have rather similar effects in trap gettering the concentration of the M3, M6 and H2. This suggests that these traps are in some way related to ($V_{As}V_{Ga}$) complexes or ($V_{As}XV_{Ga}$) complexes.

Homojunction GaAs bipolar transistors npn and pnp have been fabricated with base layers containing In isoelectronic doping and are found to have significantly better characteristics than if the In is omitted.

2.4. Conclusions

Methods of improving the characteristics of GaAs slices (LEC and horizontal Bridgman) and of MBE grown epitaxial layers have been established and studied. These improvements should impact the performance of a wide range of semiconductor GaAs devices.

Similar studies are needed for InP and for ternary and quaternary III-V semiconductors.

3. List of Publications Resulting from, or In Part From, This Grant

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4. List of Participating Scientific Personnel

- A. G. Milnes, Buhl Professor of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA.
- T. E. Schlesinger, Associate Professor of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA.
- Aizhen Li, Visiting Professor June 1987-January 1988. Professor Li is Head of the Department of Semiconductor Materials at Shanghai Institute of Metallurgy, Academia Sinica, Shanghai, China.
- J. H. Zhao, earned Ph.D. degree April 1988 and now is Assistant Professor of Electrical Engineering at Rutgers University, NJ.
- H. K. Kim, will complete Ph.D. degree by December 1989 and has accepted a position as Assistant Professor at the University of Pittsburgh, Pittsburgh, PA as of January 1990.
- D. Wong, graduate student (with partial support) will complete a Ph.D. degree by May 1990.
- Z-q Fang, Postdoctoral visitor for three years. Dr. Fang, as of September 1989, has taken a postdoctoral position with Wright State University, Dayton, Ohio.