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Principal Investigator: Professor Mulpuri V. Rao
Department of Electrical and Computer Engineering
George Mason University
Fairfax, VA 22030
Tel. 703-993-1612
Fax. 703-993-1601

Program Manager: Dr. Y. S. Park
ONR

TITLE: Planar fully ion-implanted InGaAs p-i-n photodetector

Technical Objective: Investigating the behavior of compensation implants in In-based compounds (InGaAs, InP, and InAlAs that are used in 1.2-1.6 μm fibre-optic communications) and their use in the fabrication of photodetectors.

Approach: We have performed Fe and Co implants in n-type and Ti implants in p-type InGaAs, InAlAs and InP. Selective area high resistance regions are required in multilayer device structures (like heterojunction laser, heterojunction bipolar transistors, photodetectors, etc.) that employ these three materials. Such a study is necessary with a growing interest in integrating microwave and optoelectronic devices based on these three compounds in monolithic form. The above mentioned transition metal implants were performed at both room and elevated (200 °C) temperatures. The implants were done in both keV and MeV ranges. To obtain thick high resistance layers we have also empolyed multiple energy implantations. The implanted material was annealed using a halogen lamp rapid thermal annealing station. To protect the surface during annealing, a 50 nm thick Si_3N_4 cap was used. The SIMS measurements were performed in the as-implanted and the annealed material to monitor the implant atom density depth profiles. Conventional two-probe I-V measurements were performed after depositing and alloying the Au-Ge/Au or Au-Zn/Au ohmic contacts on the n- and p-type materials, repectively. Polaron electrochemical C-V depth profiling measurements were done to get carrier concentration depth profiles in MeV energy Fe or Ti implanted InP. The RBS measurements were performed to evaluate the lattice quality of the as-implanted and annealed material.

$In_{0.53}Ga_{0.47}As$ metal-semiconductor-metal (MSM) detectors were made using: multiple energy proton bombarded (at room temperature) p-type InGaAs, multiple energy Fe implanted(at 200 °C) n-type InGaAs layer with and without 50 nm thick AlInAs Schottky barrier enhancement layer on top, and multiple energy Ti implanted (at 200 °C) p-type InGaAs with 50 nm thick AlInAs barrier. After implantation high resistance InGaAs islands were defined by photolithography and wet chemical mesa etching down to the InP:Fe substrate. Then 60 nm Ti/200nm Au multi finger interdigitated Schottky metal contacts were formed by using lift-off lithography technique. The contact pads for the devices are on the InP:Fe substrate. The metal fingers are 30 μm long and 1 μm wide with 2.5 or 3 μm separation.

The devices were tested for their D.C. I-V characteristics under dark and when subjected to a continuous 1.3 μm surface illumination at different power levels. The photoresponsivities (A/W) of the the devices at different bias voltages and illumination intensities were calculated from these characteristics and compared with the maximum theorectical values (obtained from external quantum efficiencies based on device dimensions). The responsivity of the detectors to a 1.3 μm laser pulse was studied. the typical width of the optical pulses and the system response total 45 ps and the pulse reptition rate is 100 MHz. For detectors with AlInAs Schottky barriers enhancement layer the bandwidth was measured directly.

Accomplishments: The range statistics of Fe, Co, and Ti ions in InP at MeV energies were established by analyzing the implant SIMS profiles in the as-implanted material. At MeV energies the straggle ($\triangle R_p$) value remains almost constant irrespective of the implant energy. The $\triangle R_p$ depends on the nuclear stopping mechanism. But at MeV energies the amount of energy lost by the nuclear stopping mechanism remains almost constant irrespective of the initial energy of the ion. All the excess egergy is lost by the electronic stopping mechanism which does not influence the $\triangle R_p$ value. The skewness at all MeV energies is negative indicating tilting of the implant profiles towards the surface. The kurtosis values are more than the values for no kurtosis indicating that the profiles are more pointed than the corresponding Gaussian profiles.

In InGaAs and InP during annealing the keV energy range Fe and Co implants redistributed giving satellite peaks at $0.8R_p$, $R_p + \triangle R_p$, and $2R_p$ locations. These peaks are due to (1) gettering of the implant into locations where the implant damage is maximum (2) local stoichiometric disturbances and (3) condensation of point defects into dislocation loops, respectively. Formation of the satellite peaks was avoided when the implants were performed at 200 °C. But in all three In based compounds used in this study, the Fe and Co implants out-diffuse severely (especially at keV energies) irrespective of the implant temperature. The surface electric field enhanced out-diffusion is believed to be responsible for this behavior. The out-diffusion is so severe that only a fraction of the implant remained after annealing. For MeV energy room temperature Fe and Co implants multiple peaks at the locations described above were seen in InP after annealing. The gettering of the implant to ≈ 0.7–$0.8R_p$ location acted as a reservoir for the out-diffusion of the impurity. But when the MeV implants were performed at 200 °C the buried Fe and Co implants are thermally stable during annealing. This is because of less damage in the material (which prevents gettering of the implant to peak damage location at $\approx 0.7R_p$) coupled with the fact that these implants are buried and away from the surface and hence surface electric field can not exert any force to enhance the out-diffusion of these implants.

The Ti implants in all three materials are thermally stable during annealing independent of the implant energy and implant temperature.

For the room temperature transition metal implants in InP and InGaAs the lattice damage is severe making the material amorphous at high doses. If once the material is amorphous it is not possible to obtain RBS yield close to the virgin level. Hence elevated temperature (200 °C) implantation is necessary to obtain less residual damage after annealing. For the implants performed at 200 °C the alligned RBS yield after annealing is close to the yield in the virgin sample. For the same implant conditions the implant lattice damage is relatively lower in InAlAs compared to the InP and InGaAs. In III-V compounds the resistance to lattice damage increases with an increase in Al content in the material.

In InP and InGaAs due to low solid solubility limit of the transition metals the compensation in both n- and p-type materials is effective only if the carrier concentration is $\leq 1\text{x}10^{17}$ cm^{-3}. For low carrier concentrations resistivities of $\approx 10^7$ Ω-cm in InP and $\approx 10^4$ Ω-cm in InGaAs were obtained. These values are close to the intrinsic resistivity limits in the respective materials. We have used MeV Fe and Ti implants to obtain buried high resistance regions in n-type InP substrates and also to compensate surface side tails of n-type (Si) implants in semi-insulating InP:Fe substrates. In InAlAs resistivities of $\geq 10^6$ Ω-cm were obtained by Fe and Ti implants in n- and p-type material, respectively.

We have performed multiple energy (keV to MeV range) Fe implants at 200 °C in n-type InGaAs layers to obtain high resistance over the entire depth of 1.0μm thick epitaxial layer. After 825 °C/5 s annealing only a slight out-diffusion is observed giving Fe pile up at the surface. To make devices using this material we have etched 0.1μm on the surface to remove the Fe pile up region.

The MSM detectors made on properly compensated proton bombarded p-type

InGaAs have a dark current of 5 nA at 2 V and 300 nA at 5 V bias. The D. C. responsivity in these detectors is 0.7 A/W and the impulse response full width at half maximum (FWHM) is 160 ps for 1.3 μm radiation at 5 V bias. For the MSM detector made on Fe implantation compensated n-type InGaAs the device dark current is 250nA at 2V bias, and the d.c responsivity is 0.375 A/W at 1.3 μm. The FWHM of the impulse response of the detector is 260 ps. Inspite of high resistance material used in the above detectors the break down voltage is only 5V. To improve the breakdown voltage we have used a 50 nm thick InAlAs schottky barrier on both n- and p-type InGaAs. We then performed Fe and Ti implants in the n- and p-type material, respectively. This resulted in an improvement in the breakdown voltage. The responsivity in the p-type detector has decreased from 0.2 A/W without implantation to 0.03 A/W with Ti- implantation. The responsivity in the n-type detector is 0.4 A/W without Fe implnatation, but improved to 2.3 A/W in the Fe- implanted material. While a bandwidth of about 2GHz is measured in the unimplanted material its value has decreased almost a decade in the implanted material.

Significance: Based on the above results we can conclude that compensation implantation gives detectors with good responsivity. The speeds are inferior in these devices compared to values reported in literature without compensation. This probably is due to residual lattice damage left in the material after implantation. High annealing temperatures and long annealing times can not be used due to out diffusion problem associated with Fe and Co implants in In based III-V s. If the compensation is achieved during epitaxial growth itself this problem probably could be avoided. But selective area doping can not be achieved with epitaxial doping as in case of ion-implantation. Since good responsivities are obtained in detectors made of undoped and in-situ transition metal doped material, implant compensated material does not seem attractive for detector applications where the implanted regions are the active regions of the device. But results of this work probably are more useful for GRINSCH lasers to obtain electrical charge and optical confinement which improves the device performance.

Publications:

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Participants:

Faculty - M.V.Rao

Principal Graduate Students: S.M. Gulwadi, J.M. Martin, J. Vellanki, and R.K.

Nadella.

Collaborators: N. Papanicolaou (NRL) and W.-P. Hong (Bellcore).

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