Title

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Authors

Jones, R.E.
van Genuchten, H.C.M.
Yu, K.M.
et al.

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R.E. Jones[1,2], H.C.M. van Genuchten[1], K.M. Yu[1], W. Walukiewicz[1], S.X. Li[1,2], J.W. Ager III[1], Z. Liliental-Weber[1], E.E. Haller[1,2], H. Lu[3] and W.J. Schaff[3]

[1]*Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA*
[2]*Dept. of Materials Science and Engineering, University of California, Berkeley, CA 94720 USA*
[3]*Dept. of Electrical Engineering and Computer Science, Cornell University, Ithaca, NY 14853 USA*

Abstract. InN films grown by molecular beam epitaxy have been subjected to 2 MeV He^+ irradiation followed by thermal annealing. Theoretical analysis of the electron mobilities shows that thermal annealing removes triply charged donor defects, creating films with electron mobilities approaching those predicted for uncompensated, singly charged donors. Optimum thermal annealing of irradiated InN can be used to produce samples with electron mobilities higher than those of as grown films.

Keywords: Indium nitride, doping, radiation damage, electrical properties, native defects
PACS: 61.82.Fk, 73.61.Ey

INTRODUCTION

Despite considerable interest and a substantial research effort, the transport properties of InN are not yet understood. InN has an extreme propensity for n-type doping that has been explained by a low formation energy of donor impurities and defects, due to the unusual location of the Fermi level stabilization energy high in the conduction band [1]. Nominally undoped InN films have electron concentrations (*n*) of 10^{17} to 10^{20} cm^{-3}, and electron mobilities (μ) that approach 2400 cm^2/Vs at lower values of *n*. The low formation energy of native donor defects may be exploited to increase *n* in InN films in a controlled manner using high-energy particle irradiation. For 2 MeV H^+ and He^+ ions, a linear relationship between radiation dose and the increase in *n* has been determined up to the saturation value of *n* (~ $4x10^{20}$ cm^{-3}) [1]. In addition, μ in samples irradiated with high fluences (i.e. 1.1 $x10^{14}$ 2 MeV He^+/cm^2 and higher) is controlled by scattering by the ionized donor defects [2]. Here we show that rapid thermal annealing (RTA) can improve the transport properties of these defect-doped films.

EXPERIMENTAL METHODS

Single crystal InN films (1.8 μm) were grown by molecular beam epitaxy on c-sapphire substrates with a GaN (250 nm)/AlN (10 nm) buffer layer [3]. Electrical properties of the films were determined by Hall effect measurements using a 3000 Gauss magnet. Indium contacts were made in the van der Pauw configuration. The as-grown films had electron concentrations of $6x10^{17}$ to $1x10^{18}$ cm^{-3} and electron mobilities of 500 to 1100 cm^2/Vs.

The method of high-energy particle irradiation with a 2 MeV He^+ ion beam to generate native point defects has been described elsewhere [1]. The fluence of ions ranged between $1.1x10^{14}$ and $8.9x10^{15}$ cm^{-2}. Rapid thermal annealing (RTA) was performed with a Heatpulse 10T-02 Rapid Thermal Pulsing System with flowing N_2 gas. The indium contacts used for the Hall effect measurements were removed prior to annealing by etching in HCl. The samples were sequentially annealed at 375°C (not all samples), 425 °C and 475°C for increasing time intervals from 10 to 300 seconds. The electrical properties were measured after each anneal. RTA treatments at temperatures of 500°C and higher were also performed on the samples, but film delamination from the GaN buffer layer was observed.

RESULTS

Figure 1 shows μ and *n* in the studied films at each experimental stage (as-grown, irradiated with 2 MeV He^+ ions, and thermally annealed after irradiation). It can be seen that irradiation produces a narrow distribution of μ as a function of *n* that can be well explained as controlled by scattering from triply charged donor defects [2]. The increased deviation of the theoretical mobilities from experimental values at concentrations above 10^{20} cm^{-3} may be attributed to resonant short range scattering. A static dielectric constant of 9.3 in the calculations of theoretical μ was assumed [4]. After the series of RTA treatments, μ lies well above the theoretical line for triply charged defects, and moves toward the line for μ limited by uncompensated, singly charged defect scattering. Overall, n is halved and μ increases by a factor of four as a result of the RTA treatments. It is noteworthy that in irradiated and annealed films, μ can approach and even exceed the values of the as-grown films, with n at least an order of magnitude higher. Further, the values of μ exceed those of as-grown InN films at comparable n, suggesting irradiation followed by thermal annealing as a technique for creating InN films with improved transport properties.

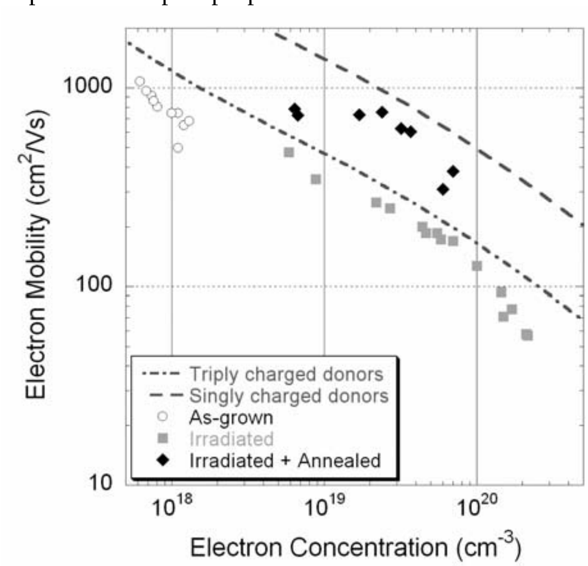

FIGURE 1. Electron mobility as a function of concentration in the studied samples after each of the experimental stages. Theoretical values for mobility limited by scattering from triply and singly charged defects are also shown.

The effect of annealing on μ may be explained by the presence of two different types of donor-like defects: triply charged defects that are partially removed by annealing, and stable, singly charged defects. Modeling of the annealing results provides qualitative support for this explanation. We have recently proposed that the singly charged defects are nitrogen vacancies and the triply charged defects are relaxed indium vacancies [2].

Irradiation at high fluences has been shown to diminish photoluminescence (PL) in InN [5]. RTA treatments after irradiation at high fluence generate a recovery of PL, which is consistent with the measured decrease in n (Fig. 2).

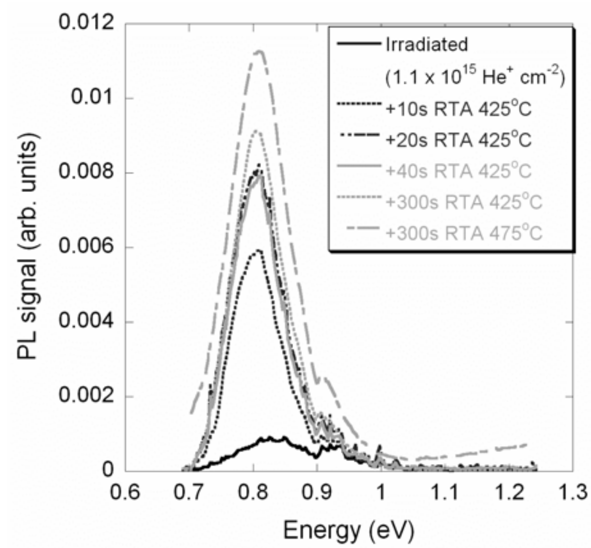

FIGURE 2. Photoluminescence of one InN film after irradiation and then sequential RTA treatments.

CONCLUSIONS

We have shown that rapid thermal annealing of irradiated InN produces films with high electron mobilities, and recovers photoluminescence. This result may be attributed to the removal of triply charged, relaxed indium vacancies and the stability of singly charged nitrogen vacancies.

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