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He implantation induced defects in InN.

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Abstract. In N layers have been implanted with helium at 158 keV at various fluences to study the nature of the generated defects. The defects have been probed using positron annihilation spectroscopy. The first measurements showed that at least two different kinds of defects are created depending of the implantation fluence. The second measurements performed two years later gave different results suggesting that at least one of these defects is not stable at room temperature.

1. Introduction

InN is a significant semiconductor with many interesting properties such as low direct band gap (0.7 eV) [1–5] and high electron mobility promising applications in optoelectronics and high-speed electronics [6–8]. The presence of intrinsic point defects can change the electrical properties of the material in an advantageous way or not: In vacancies (V_{In}) and N vacancies (V_N) are expected to be the dominant intrinsic acceptors and donors, respectively, according to latest density functional theory calculations. The understanding and control of these defects is consequently an important element in the development of the industrial applications. Despite major research efforts in that area, relatively little is known about the properties of defects in In N especially their annealing temperature.

High-energy particle irradiation has been demonstrated as an effective way to control the conductivity of undoped InN by creating defects. The implantation of InN with helium could be an effective tool for precise control of In vacancy concentration without the risk of unintentional doping. In the frame of a more global work on the effects of the different defects on the InNs electrical properties, we have studied the defects generated by He-ions implantation in this material. The damaged zones of the implanted samples have been probed using the positron annihilation spectroscopy. The samples have been probed twice with a delay of 2 years. The measurements show an evolution of the defects detected by positrons. These never before observed changes will be discussed.

2. Experimental techniques

The studied samples are undoped 2 μ m layer of InN grown on GaN wafer by plasma-assisted molecular beam epitaxy (n=5×10¹⁷ cm⁻³, μ =1500 cm²V⁻¹s⁻¹), implanted with 158 keV-He ions at three fluences 8×10^{12} , 8×10^{14} and 8×10^{15} cm⁻² at room temperature in the University of Helsinki. Both damage and He-implantation depth profiles calculated using SRIM 2013 in full damage cascade calculation mode are plotted figure 1. The projected range is at about 580 nm. The Doppler broadening measurements of the positron-electron annihilation radiation were performed with a variable-energy positron beam on an energy range from 0.5 to 35 keV with high-purity Ge detectors. The positron implantation depth profiles drawn figure 1-a show that up to 15 keV positrons probed only damaged area then they start probing the undamaged one behind the He peak. From 25 keV, positrons can reach the GaN substrate. The conventional low-momentum (S) and high-momentum (W) annihilation parameters have been used to analyse the data [9].



Figure 1. a) Vacancy and He concentration depth profiles as calculated using SRIM 2013. Positron implantation depth profile are plotted for positron energy from 2 to 20 keV. First results: b) and c) Normalized S and W parameter values as a function of positron energy. d) W as a function of S parameter for positron energy from 4 to 20 keV. The full square symbol represents the positron annihilation characteristics in the V_{In} as reported by Rauch et al. [10].

3. Results and discussion

3.1. First measurements

The results of the measurements performed two weeks after implantation are plotted in figure 1. S and W parameters values are normalized with those of the as-grown sample ones that coincide with the InN lattice values [10] ($S_{AG} = 0.460 \pm 0.001$, $W_{AG} = 0.0491 \pm 0.0008$). The figure 1-b. shows the S parameter as a function of the positron energy. The as-grown curve can be shared in three parts: up to 3 keV positrons probe a part of the surface, between 4 and 25 keV the plateau corresponds to the bulk of the InN layer, and after 25 keV, S decreases because positrons start probing the GaN substrate layer. In the case of implanted samples, one can observe that whatever the fluence, the S value is higher than that of the as-grown sample that means defects are detected. At the fluence of 8×10^{12} cm⁻², S (resp. W) values form a plateau

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up to energy of 15 keV where it starts slightly decreasing (resp. increasing). At the fluence of 8×10^{13} cm⁻², the S and W values are respectively higher and lower than the previous fluence ones and the curves shapes are different. The S values slightly increase and start decreasing clearly for positron energies higher than 20 keV. The W curve decreases strongly between 5 and 15 keV then increases up to 35 keV. Finally at the fluence 8×10^{15} cm⁻², the S values seems to form a plateau up to 12 keV then decrease progressively in the range 15-25 keV.

In the figure 1-d the W parameter is plotted as a function of the S one for the positron energy range 4-20 keV corresponding to the damaged area. The (S, W) points for the three fluences are not aligned with the InN reference point (1, 1) indicating that the defects detected by positrons have different nature. For the lowest fluence, the points form a straight line named (D_1) . For the highest fluence, the points are grouped close to the point V_{In} giving the positron annihilation characteristics in the Indium vacancy [10], suggesting that this defect is detected by all the positrons. In the case of the intermediate fluence, the (S, W) points are not aligned with the as-grown sample annihilation characteristics indicating that more than one type of defect is detected. These points being partly on the $(InN-V_{In})$ line, one of these defects could be the V_{In} one. The rest of the points form a line (D_2) with the InN reference point.



Figure 2. Positron results after 2 years of storage in air. a) and b) Normalized W and S parameter values as a function of positron energy for the three fluences and the as-grown reference sample. c) W as a function of S parameter. d) Comparison of data obtained before and after storage for 2 years.

3.2. Measurements 2 years after

The figure 2 shows the results of the Doppler broadening measurements performed two years after the implantation, with the samples stored in ambient conditions. The S and W curves have significantly changed. For the sample implanted with the lowest fluence, the S and W parameter values are equivalent to those of the as-grown sample meaning that no vacancy-type defect is detected. At the highest fluence, the S and W curves have the same shape than for the previous measurements but the S and W values are both lower in the whole positron energy range. For

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instance, the plateau between 4 and 10 keV clearly decreases for the S parameter (figure 1-b and figure 2-b). That indicates a change in the defect distribution. For the intermediate fluence, the main change occurs in the first part under the surface, for positron energy up to 10 keV. The S (resp. W) parameter values have decreased (resp. increased) to merge with the InN reference ones. The second parts of the curves are roughly as the previous ones. In the figure 2-c showing the evolution of the W parameter as a function of the S one, one can observe that all the (S, W) points are aligned with the as-grown reference point. The error bars indicated for the Indium vacancy annihilation characteristics suggest than this vacancy might be also on the same line.

3.3. Comparison and discussion

The figure 2-d allows us to compare the positron annihilation states observed in both cases. From three lines defined by the (S, W) points during the first measurements, $(D_1), (InN-V_{In})$ and (D_2) , just (D_2) is remaining after two years. The annihilation state observed at the lowest fluence disappeared and no other defect are detected. At the intermediate fluence, a part of the points which were on the (D_2) line are still there but the other part which was between the (D_1) and the (D_2) lines are now only on the (D_2) line. It is the same at the highest fluence for which all the points moved from the $(InN-V_{In})$ line to the (D_2) line. These observations suggest that at least three annihilation states were detected during the first measurements: the lattice and two vacancy type defects. Indeed in the case of the high fluence, the annihilation states observed could be a mixture of those generating the (D_1) and the (D_2) lines respectively called V_X and V_Y . On the other hand, these results highlight that after 2 years, the defect V_X has disappeared indicating that it is not stable at room temperature.

4. Conclusion

In N samples have been implanted with 158 keV-He ions at three different fluences to study the nature of defects generated and their properties. The damaged layer has been probed by positron annihilation spectroscopy first just after the implantation then two years after. The first results have shown that at least two different types of vacancy defects are created. The second measurement session has highlighted that at least one of the induced defects was not stable at room temperature. Complementary analysis and experiments will be needed to identify the involved defects, but the instability of a defect at room temperature is already an interesting observation from ion implantation processing point of view.

Acknowledgments

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