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KrF Excimer Laser Doping of Si into GaN

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Abstract Silicon doping in undoped GaN has been performed by irradiating amorphous silicon film deposited by ion beam sputtering on GaN using 248 nm KrF excimer laser. Sheet resistances and depth profiles of the Si-doped GaN as functions of a number of laser pulses and laser fluence have been measured in order to clarify the relation between properties of doped GaN and irradiation conditions. The minimum sheet resistance of about 60 Ω / □ was obtained. SIMS analysis showed that Si is successfully diffused into GaN. The depths of doped regions ranging from 38 nm to 110 nm were obtained and can be readily controlled by irradiation conditions. Temperature-dependent Hall measurements for doped regions were investigated as a function of laser fluence.

Keywords GaN, Capping layer, Excimer laser doping, Sheet resistance, Dopant profile, Hall measurements

1. Introduction

GaN as a wide band gap III-V compound semiconductor has been widely studied for applications in high-power and high electron mobility transistors (HEMT's) [1-2]. High performance GaN HFET and MOSFET have been both demonstrated [3-5]. The GaN processing techniques are crucial in order to achieve good performance of GaN based devices. Most of the GaN devices are doped by ion implantation, which offers good uniformity and precise control of the dose as a function of depth and position on the substrate. However, implantation damage must be removed by a suitable annealing treatment to achieve better structural reordering and a high doping efficiency [6-8]. In production, ion implanted semiconductors have been annealed exclusively with furnaces or heat lamps. With these techniques, high temperatures are present over the entire sample, including the unimplanted layers, causing diffusion of atoms between layers. The laser doping method has been reported to produce superior device characteristics compared with other conventional doping methods. The short time duration (a few tens of nanosecond) of the ultraviolet excimer-laser pulse emitted makes it possible to confine the doped impurities to very shallow surface regions with extremely high dopant and high carrier concentrations [9-11].

By now a few published works devoted to the investigation of doping GaN substrate using an excimer laser to obtain conductive GaN [12-14]. In this paper, Si doping in undoped GaN with irradiation of 248 nm wavelength KrF excimer laser to melt amorphous silicon (a-Si) layer deposited on GaN is described. The variation of sheet resistance of doped GaN and depth profiles of silicon as functions of the laser fluences and the number of laser pulses will be discussed. Hall measurements suggested that the decrease of sheet resistance is due to the increase of charge carrier density.

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2. Experiment

Figure 1 shows the schematic cross-sectional view of the grown samples prepared for laser irradiation. First a 1.4 µm thick undoped GaN layer was grown by metalorganic chemical vapor deposition on 2 inch c-plane sapphire substrate. After this layer was grown, each sample was transferred via room ambient to ion sputtering chamber. A 60 nm amorphous silicon layer (a-Si) was deposited at room temperature, followed by 200 nm silicon dioxide (SiO_2) as a capping layer to prevent amorphous silicon from blowing up during laser irradiation. Thermal diffusion effect makes the whole SiO_2 capping layer to act as a heat capacitor and anti-reflection effect of the capping layer reduces the net light reflected from the sample [15]. Therefore the capping layer plays a role of heat capacitance for silicon melting and the diffusion of silicon into GaN during laser irradiation. The thicknesses for a-Si and SiO_2 layer were optimized to allow laser radiation to fully melt a-Si and to be absorbed by GaN allowing the diffusion of Si-atoms into GaN. The propostion of the above multilayered structure was based on thermal calculations for the prediction of a melt threshold for the energy density of the laser [16].

Figure 2 shows the irradiation system for laser doping used in the present study. A Lambda-Physik LPX-120i KrF excimer laser beam providing at 248 nm a pulse of 20 ns duration was directed nearly perpendicular to the sample surface at a repetition rate of 2 Hz. The laser fluence at the sample surface and then number of laser pulses were varied from 250 to 650 mJ/cm^2 and from 50 to 150, respectively. The laser beam has the dimensions of 21 mm 6 mm was focused using a cylindrical lens and irradiated into the doping chamber through synthetic quartz window. The beam dimensions at the sample surface were 6mm wide and 6 mm long. The irradiation was carried out at atmospheric pressure.

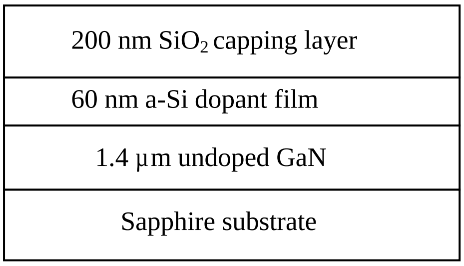

Figure 1. Schematic structure of growing samples prepared for doping

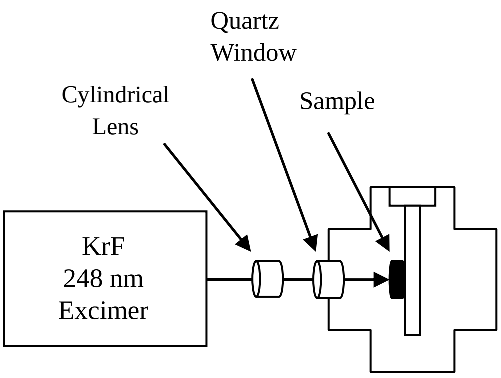

Figure 2. Schematic diagram of the irradiation system for laser doping used in the present study

After laser irradiation, the residue of SiO_2 was etched using hydrofluoric acid (HF) diluted 1:10 with water and then the residue of a-Si was etched away using the solution (1 HF: 5H2O: 20 HNO3). The depth profiles of the Si concentration of the samples were obtained by means of secondary ion mass spectroscopy (SIMS). The sheet resistance of the doped GaN layers by laser irradiation was measured using a four-point probe method. For Hall effect measurements the samples were prepared using lithographically defined van der Pauw structures. Hall effect measurements were conducted at different temperatures using magnetic fields of about 2 T. During the measurements the applied voltage was kept below 3 V to reduce any leakage through the underlying n-type GaN layer.

The electron concentration n was obtained using the relation $n = r_H / qR_H$ with the Hall scattering factor r_H assumed to be a unity.

3. Results

3.1. Sheet Resistance of Si Doped GaN

Figure 3 shows the variations of sheet resistance as a function of the number of laser pulses at laser fluence of 650 mJ/cm^2. It can be seen that increasing the number of pulses decreases the sheet resistance. Successive pulses add thermal energy to the surface and this should result in an increase of the lateral conduction of heat and hence the diffusion time so that more dopant can be incorporated into the GaN layer. Figure 4 shows sheet resistance versus laser fluence at 100 pulses. We see that increasing the pulse energy decreases the sheet resistance. It is believed that, as long as the dopant source has not been consumed, the higher the irradiation intensity the more dopant atoms can be incorporated into the GaN surface due to a larger melt depth [17], and because the time during which the layer is molten get longer, which could allow accommodation of more dopant atoms. The laser fluence was limited to 650 mJ/cm^2 to avoid ablation of SiO_2.

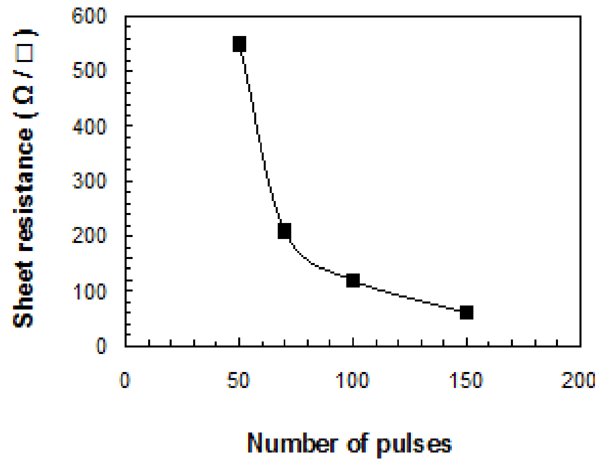

Figure 3. The sheet resistance versus number of pulses for doped GaN layers made with laser fluence 650 (mJ/cm^2)

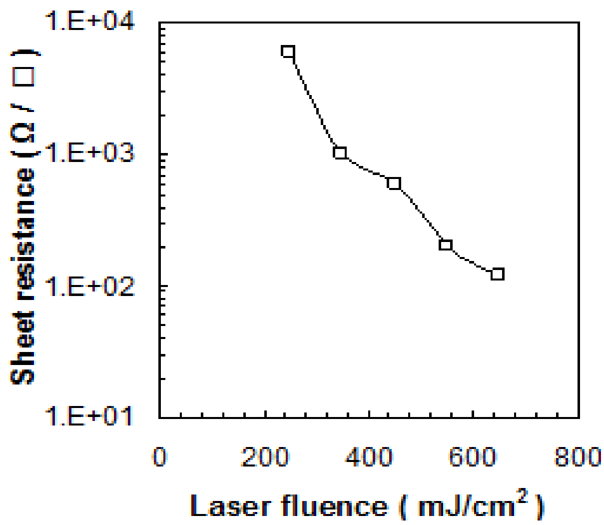

Figure 4. Sheet resistance versus laser fluence for doped GaN layers fabricated with 100 pulses

3.2. Dopant Depth Profile

Si concentration and its depth profile for doped GaN layers were revealed by SIMS measurements. Figure 5 shows the concentration profiles of incorporating Si atoms for GaN layers made with 100 pulses at different laser fluences. The peak concentrations of Si were as high as (2-4) $\times 10^{20}$cm^{-3} at the surface for all samples. We see that increasing laser fluence causes Si-atoms to extend deeper, suggesting that doping depth is controlled easily by laser fluence. Increasing laser fluence increases the diffusion time and then allowing the Si atoms to diffuse deeper [18-19].

The depth of the doped region which is defined as the distance from the surface where the one-thousandth of surface concentration extrapolated in Figure 5 was found to be less than 105 nm even at laser fluence of 650 mJ/cm^2. The minimum doping depth of 38 nm was obtained at laser fluence of 250 mJ/cm^2. Thus, it is possible to fabricate shallow junction of desirable depth by selecting suitable laser fluence.

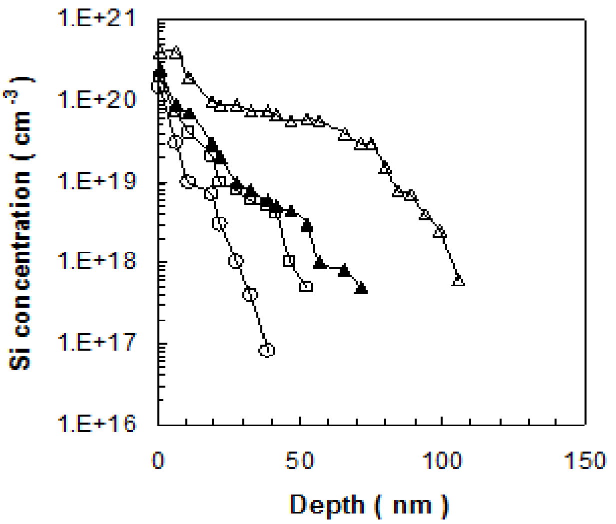

Figure 5. Si concentration depth profile for doped GaN layers made at 100 pulses with different laser fluences: (Δ) 650 (mJ/cm^2), (▲) 450 (mJ/cm^2), (□) 350 (mJ/cm^2), (○) 250 (mJ/cm^2)

3.3. Hall Measurements

Hall measurements were used to determine the electron concentration with their ionization energy for Si-doped GaN layers. Figure 6 shows the carrier concentration (averaged over the whole thickness of the GaN layer) versus temperature for three samples made at 100 pulses with different laser fluences.

The concentration increases with laser fluence as would be expected from SIMS data. The electron concentration for samples made with laser fluences 550 and 650 mJ/cm^2 maintained at approximately (3-7) $\times 10^{19}$ cm^{-3} even at low temperature. Therefore, the ionization energy was almost zero for these samples. In other words, electron concentration is independent of temperature. This phenomenon is usually observed in highly doped semiconductors since the impurity band is widened and merged with the conduction band in highly doped semiconductors [20]. In Figure 6, it can be seen that the carrier concentration in the GaN layer made with laser fluence of 450mJ/cm^2 showed little variation with temperature exhibiting activation energy E_a of about 40 meV. We see that increasing the laser fluence leads to an increase in average electron concentration which is in agreement with SIMS results. Dopant atoms are incorporated by a combination of mixing and diffusion, as the laser fluence increases, the time during which the layer is molten increase and the molten zone becomes deeper. Consequently, more dopant atoms are incorporated into GaN due to larger melt depth, resulting higher average carrier concentration. By changing the laser fluence we can control the average carrier concentration.

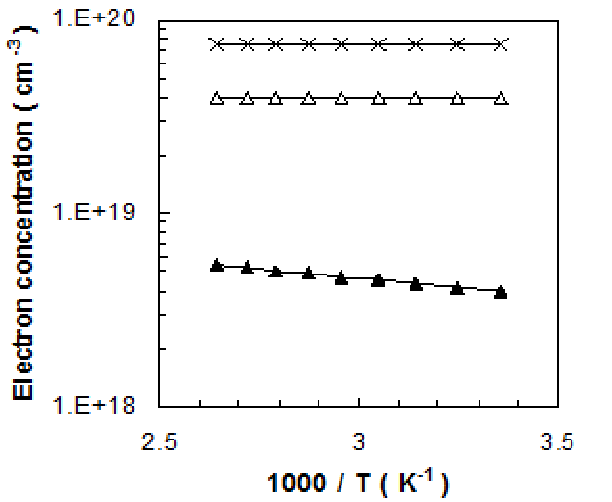

Figure 6. Electron concentration as a function of inverse temperature for doped GaN layers made at 100 pulses with different laser fluences: (×) 650 (mJ/cm^2), (Δ) 550 (mJ/cm^2), (▲) 450 (mJ/cm^2)

4. Conclusions

We have successfully demonstrated Si doping of GaN using a KrF excimer laser method. Dopant atoms were driven into the GaN from pre-deposited a-Si film during irradiation at atmospheric pressure. The laser irradiation causes the amorphous silicon to melt and to be diffused into GaN. Sheet resistance decreases with increasing laser fluence and the number of pulses. The minimum sheet resistance of 60 Ω/□ was obtained at 100 pulses with laser fluence 650 mJ/cm^2. By changing the laser fluence and the number of pulses we can control the sheet resistance. SIMS analysis showed a depth of the doped region of about 105 nm. The average dopant concentration can be readily controlled by varying laser fluence. Hall measurements showed a maximum carrier concentration of about 7×10^{19} cm^{-3} with almost zero ionization energy obtained at 100 pulses with laser fluence 650 mJ/cm^2. It has been shown that KrF excimer laser doping makes possible to fabricate highly conductive GaN layers. The process offers simplicity of operation without the need for sophisticated equipment.

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REFERENCES

[1] Y. C. Chang, “Drain current enhancement and negligible current collapse in GaN MOSFETs with atomic-layer-deposited HfO_2 as a gate dielectric,” Microelectronic Engineering, vol. 87, pp. 2042-2045, 2010.

[2] M. J. Davies, P. Dawson, F. C-P. Massabuau, R. A. Oliver, M. J. Kappers, and C. J. Humphreys, “The effects of Si-doped prelayers on the optical properties of InGaN/GaN single quantum well structures,” Appl. Phys. Lett., 105, 092106, 2014.

[3] S. Oktyabrsky and P. D. Ye, “Fundamentals of III-V semiconductors MOSFETs,” Springer Science+Business Media LLC, 2010.

[4] C. T. Lee, “GaN-based Metal-Oxide-Semiconductor Devices,” in Semiconductor Technologies, J. Grym, InTech, 2010, pp. 151-208.

[5] P. G. Chen, M. Tang, M. H. Lee, "Indium-Based Ternary Barrier High-Electron- Mobility Transistors on Si Substrate With High ON/OFF Ratio for Power Applications,” IEEE Electron Device Lett., vol 36, no. 3, pp. 259 – 261, March 2015.

[6] J. K. Sheu, “n+-GaN formed by Si implantation into p-GaN,” J. Appl. Phys., vol. 91, pp. 1845-1848, 2002.

[7] H. Yu, “Dopant activation and ultralow resistance ohmic contacts to Si-ion-implanted GaN using pressurized rapid thermal annealing,” Appl. Phys. Lett., vol. 85, pp. 5254-5256, 2004.

[8] P. Suvarna, J. Bulmer, J. M. Leathersich, J. Marini, I. Mahaboob, J. Hennessy, L. D. Bell, S. Nikzad, F.S. Shahedipour-Sandvik, “Ion Implantation-Based Edge Termination to Improve III-NAPD Reliability and Performance,” IEEE Photonics Technology Lett., vol. 27, no. 5, pp. 498-501, 2015.

[9] E. A. Al-Nuaimy and H. Abdulqader, “BJT Fabrication using excimer laser assisted spin-on doping,” Journal of Electron Devices, vol. 6, pp. 197-202, 2008.

[10] E. A. Al-Nuaimy and J. M. Marshall, “Excimer laser crystallization and doping of source and drain regions in high quality amorphous silicon thin film transistors,” Appl. Phys. Lett., vol. 69, pp.3857-3859, 1996.

[11] K. Sugioka and K. Toyoda, “Generation mechanism and thermal stability of high carrier concentration by KrF-excimer laser doping of Si into GaAs,” Appl. Phys. A, vol. 59, pp. 233-237, 1994.

[12] S. C. Lee, J. C. Her, S. M. Han, K. S. Seo, and M. K. Han, “Low-Resistance Ti/Al/Ni/Au Ohmic Contact of GaN Employing Silicon Diffusion by XeCl Excimer Laser Irradiation,” Electrochem. Solid-State Lett., vol. 8, pp. G135-G136, 2005.

[13] S. J. Rhee, S. Kim, C. W. Sterner, J. O. White, and S. G. Bishop, “Excimer laser annealing of Er-implanted GaN,” J. Appl. Phys., vol. 90, pp. 2760-2763, 2001.

[14] Y.J. Lin, W. F. Liu, and C. T. Lee, “Excimer-laser-induced activation of Mg-doped GaN layers,” Appl. Phys. Lett., vol. 84, pp. 2515-2517, 2004.

[15] Masato Hiramatsuz, Hiroyuki Ogawa, Masayuki Jyumonji, Tomoya Katou, Noritaka Akita and Masakiyo Matsumura, “An Advanced Sample Structure for Large-Grain Growth by Excimer Laser Crystallization,” J. Electrochem. Soc. 2006 153 (10): G883-G886.

[16] J. Förster, and H. Vogt, “Excimer Laser-Annealing of Amorphous Silicon Layers,” Proceedings of the COMSOL Conference 2011 Stuttgart (2011).

[17] K. G. Ibbs and R. M. Osgood “Laser Chemical Processing for microelectronics,” Cambridge University Press, 1989. p. 156.

[18] S. Coutanson, E. Fogarassy, and J. Venturini “Mechanisms and application of the Excimer laser doping from spin-on glass sources for USJ fabrication,” Applied Surface Science vol. 252, Issue 13, 30 April 2006, Pages 4502–4505.

[19] M. M. Hossain, M. H. Chowdhury, “Heat transfer simulations for pulsed laser annealing of silicon thin film,” Circuits and Systems (MWSCAS), 2013 IEEE 56th International Midwest Symposium on, 4-7 Aug. 2013, pp. 732 - 735

[20] N. F. Mott, “Metal-Insulator Transitions,” Taylor & Francis, London, 1990.