Vol 14 No 10, October 2005
1009-1963/2005/14(10)/2133-04

Chinese Physics

© 2005 Chin. Phys. Soc.
and IOP Publishing Ltd

Photoluminescence characteristics of GaN:Si*

Feng Qian(冯 倩)[a)b)], Gong Xin(龚 欣)[a)],
Zhang Xiao-Ju(张晓菊)[a)], and Hao Yue(郝 跃)[a)]

[a)] *Research Institute of Microelectronics, Xidian University, Key Laboratory of Ministry of Education for Wide Gap Semiconductor Materials and Devices, Xi'an 710071, China*

[b)] *School of Telecommunications Engineering, Xidian University, Xi'an 710071, China*

(Received 24 March 2005; revised manuscript received 30 May 2005)

Both the electrical and optical properties are studied of the GaN:Si films with carrier concentrations ranging from 10^{17}cm^{-3} to 10^{19}cm^{-3}.The results indicate that the increase in slope of carrier concentration starts to slow down when the flow rate of SiH_4 is larger than 6.38μmol/min, which is attributed to the amphoteric character of Si. At the same time, the photoluminescence results show that the FWHM of UV is widened, which can be interpreted quantitatively with a semi-classic model. Furthermore, the intensity ratio between the yellow and the UV luminescences reduces monotonically with Si dopants increasing.

Keywords: GaN:Si, heteroepitaxy, Hall, photoluminescence
PACC: 7830, 6855, 6110

1. Introduction

Wide band-gap III-V nitride semiconductors have attracted one's interests because of their tremendous applications to short wavelength optoelectronic devices. Among them, gallium nitride(GaN) is a potential candidate as a primary material for the future blue, violet and ultraviolet light emitting diodes and laser diodes. The excellent thermal properties and inert surfaces of nitrides also make them have a high priority as ideal candidates for high-temperature and high-power devices.[1−5] As capable of introducing shallow donor level and the low activation energy, Si is always used as a donor element in GaN films.

In this paper, we perform the Hall and PL measurements in a set of the Si-doped GaN epifilms. Our experimental results reveal that the photoluminescence line of the UV widens as the doping concentration increases. The broadening is interpreted in terms of potential fluctuations caused by the random distribution of donor impurities, on the other hand, the intensity ratio between the yellow and the UV luminescences reduces, which is due to the reduce in V_{Ga} concentration.

2. Experiments

The GaN:Si films used as samples in this study were grown by metallic organic chemical vapour deposition (MOCVD) at 2.0×10^4Pa on sapphire substrates. Trimethylgallium (TMGa) and NH_3 were used as precursors. To improve the structural properties of the films, the deposition of the GaN active epilayer on the 25nm thick GaN buffer layer grown at 550°C was carried out at a substrate temperature of 1040°C .The films were about 2.2–2.4μm thick. All the films were grown under exactly the same condition except for the silane (SiH_4) flow rate to achieve doping densities in the range from 10^{17}cm^{-3} to 10^{19}cm^{-3}. For the photoluminescence measurements, the samples were excited by a He-Cd laser emitting at 325nm. A 0.85m monochromator, a photomultiplier tube, and standard lock-in technique were used to detect the photoluminescence signal.

3. Results and discussion

Figure 1 shows the relationship between the electron concentration and mobility and the flow rate of SiH_4. As the flow rate increases, the carrier mobility decreases monotonously, which is due to the scattering effect of much more ionized dopants on the electrons and the enhancement of crystal lattice vibration scattering introduced by further crystal imper-

*Project supported by the State Key Development Program for Basic Research of China(973) and the National Advanced Research Program (Grant No 41308060106).

fection. While the flow rate is less than 0.6μmol/min, the electron concentration is proportional to the flow rate, the increasing rate of the concentration slows down gradually with flow rate increasing and the carrier concentration approaches saturation for the rate larger than 6.38μmol/min. The reason for this phenomenon is the amphoteric character of Si element. Under the high doping condition, some Si atoms would substitute N site and become acceptor and induce self-compensation, which always occurs in III-V semiconductors , such as GaAs and GaInP with a doping level of 10^{18}cm^{-3}.Thus we suggest that the saturation is also caused by self-compensation.

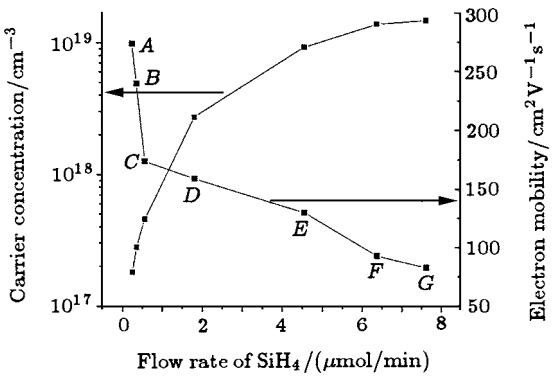


Fig.1. The relationship between the flow rate of SiH_4 and the electron concentration and mobility.

The photoluminescence spectra of some Si-doped GaN samples at room temperature are shown in Fig.2. The spectra display an intense UV transition which has been assigned to band-to-band recombination as well as to excitonic recombination.[6–8] We can also see that the near-band edge luminescence line broadens as doping concentration increases, which can be interpreted as follows.

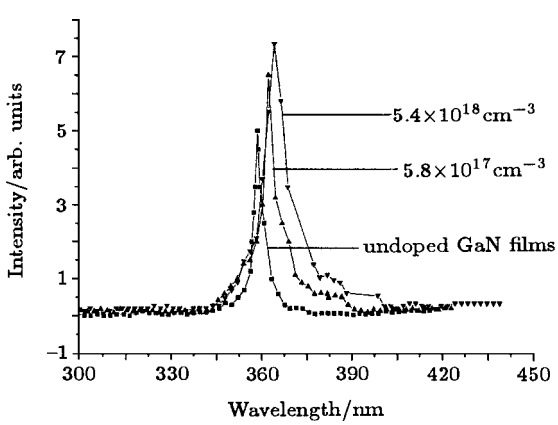


Fig.2. Photoluminescence spectra of GaN:Si samples at room temperature.

When Si is doped into a GaN film, randomly distributed dopants unavoidably causes the doping concentration to fluctuate on a microscopic scale. These microscopic concentration fluctuations result in potential fluctuations. If these potential fluctuations are sufficiently large, a noticeable broadening of luminescence lines will occur. Therefore it is the random distribution of Si that induces the broadening. In order to investigate the effect of potential fluctuation on luminescence width quantitatively, we take the semiclassic model and the effect is limited in distance to the screening radius.

The total charge number of donor and acceptor within the sphere determined by the screening radius is given by[9,10]

$$Q = e(N_{\rm A} + N_{\rm D})(4/3)\pi r_{\rm s}^3,$$

where $N_{\rm A}$ is the acceptor concentration, $N_{\rm D}$ is the donor concentration, $r_{\rm s}$ is the screening radius and defined as

$$r_{\rm s} = \left[-\left(\frac{{\rm d}n}{{\rm d}V}\right)_{v=0} \frac{e}{\varepsilon} \right]^{-1/2}.$$

Assuming that dopants are of Poisson-distribution, the mean charge fluctuation is given by

$$\Delta Q = \sqrt{e(N_{\rm A} + N_{\rm D})(4/3)\pi r_{\rm s}^3},$$

then the potential fluctuation at the location $\boldsymbol{r}$, caused by the charge dQ located at $\boldsymbol{r}_{\rm i}$, is given by

$${\rm d}\Phi(\boldsymbol{r} - \boldsymbol{r}_{\rm i}) = \frac{{\rm d}Q}{4\pi\varepsilon\,|\boldsymbol{r} - \boldsymbol{r}_{\rm i}|} \exp\left[-\frac{|\boldsymbol{r} - \boldsymbol{r}_{\rm i}|}{r_{\rm s}} \right],$$

where ε is the permittivity of GaN. By integrating over all the differential charges, we obtain the total potential deviation

$$\Phi(\boldsymbol{r}) = \int_V \frac{{\rm d}Q}{4\pi\varepsilon\,|\boldsymbol{r} - \boldsymbol{r}_{\rm i}|} \exp\left[-\frac{|\boldsymbol{r} - \boldsymbol{r}_{\rm i}|}{r_{\rm s}} \right].$$

The average potential deviation is then given by

$$\Delta\Phi = \frac{1}{V}\int_V \Phi(\boldsymbol{r}){\rm d}V,$$
$${\rm d}V = 4\pi\,|\boldsymbol{r}|^2\,|{\rm d}\boldsymbol{r}|.$$

Assuming that the entire fluctuating charges are located at the center of the sphere, the potential fluctuation at $r = (3/4)r_{\rm s}$ is then given by

$$\Delta\Phi = \frac{2e}{3\varepsilon}\sqrt{(N_{\rm D} + N_{\rm A})\frac{r_{\rm s}}{3}}e^{-3/4}.$$

Then the FWHM of the UV luminescence is given by

$$\Delta E_{\rm FWHM} = \frac{2e^2}{3\pi\varepsilon}\sqrt{(N_{\rm D} + N_{\rm A})\frac{\pi r_{\rm s}}{3}}e^{-3/4}2\sqrt{2\ln 2},$$

where the factor $2\sqrt{2\ln 2}$ accounts for the difference between the standard deviation and the FWHM of a Gaussian distribution.

From Fig.2, we obtain the FWHM of undoped GaN being 35meV, which includes the crystal imperfection broadening and thermal broadening. The experimental data and theoretical results are compared in Fig.3. In the range of doping concentrations, the measured broadening is in excellent agreement with the calculated broadening due to potential fluctuations caused by the random distribution of dopants. On the other hand, we find that the intensity ratio between the yellow-band luminescence and the UV band luminescence decreases monotonically as doping level increases, as shown in Fig.4.

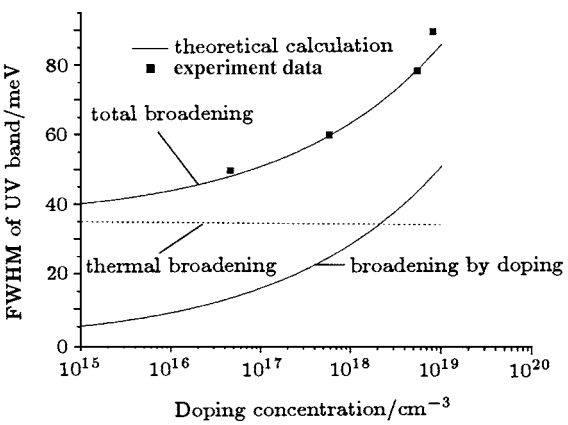


Fig.3. The broadening of UV band by Si doping.

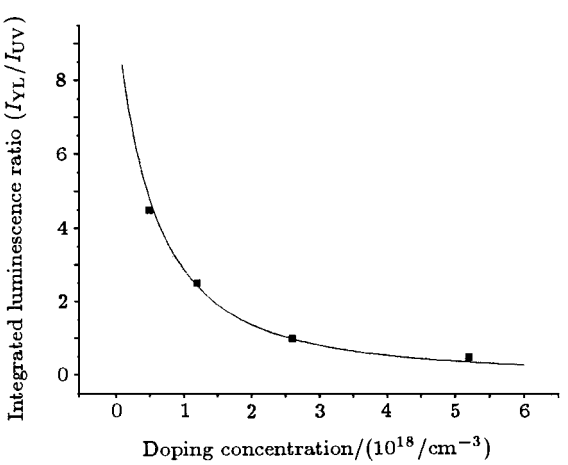


Fig.4. The ratio of the I_{YL} to the I_{UV} as a function of doping concentration.

This behaviour implies that the number of YL-related defects decreases with the increase of Si dopants. According to many previous results of the PL measurements, it is found that the YL emission may originate from a transition from shallow donors to acceptors like deep levels. Based on this result, the intensity of the UV luminescence, a near band-edge transition, can be expressed by

$$I_{\mathrm{UV}} = Bnp = BN_{\mathrm{D}}p,$$

and the intensity of the YL, a shallow-donor-to-deep level transition, is given by

$$I_{\mathrm{YL}} = CnN_{\mathrm{A}} = CN_{\mathrm{D}}N_{\mathrm{A}},$$

where B and C are the probabilities for the corresponding radiative recombinations respectively, p is the concentration of holes ($p \gg p_0$, where p_0 is the intrinsic hole concentration.), N_{D} is the doping concentration (assuming $n = N_{\mathrm{D}}$) and N_{A} is the concentration of the acceptor-like deep level. In general, the deep level concentration depends on the doping concentration according to the power law[11]

$$N_{\mathrm{A}} \propto (N_{\mathrm{D}})^i,$$

then the luminescence ratio is given by

$$\frac{I_{\mathrm{YL}}}{I_{\mathrm{UV}}} \propto N_{\mathrm{A}} \propto (N_{\mathrm{D}})^i.$$

Using the above equations, the power i measured in Fig.4 is about –1.8. Thus, the yellow luminescence defect is found to decrease as doping concentration increases. Our result is consistent with that from the model that the microscopic origin of the yellow emission can be attributed to the V_{Ga}. Due to the substitution of Si dopants on gallium lattice sites, the number of V_{Ga} decreases, and hence the YL related defects also decrease.

4. Conclusion

The electrical and optical properties of GaN:Si films have been investigated for Si doping concentrations ranging from $10^{17}\mathrm{cm}^{-3}$ to $10^{19}\mathrm{cm}^{-3}$. The FWHM of band-to-band transition increases monotonously as the doping concentration increases, which is interpreted quantitatively by a semi-classic model which takes into account the potential fluctuation caused by the random distribution of donor impurities. Otherwise, the intensity ratio between the yellow and the UV luminescences reduces, which is ascribed to the substitution of Si dopants in V_{Ga}.

References

[1] Zhang J F, Zhang J C and H Y 2004 *Chin. Phys.* **13** 1334

[2] Zhang H X, Lu H M, Ye Z Z *et al* 1999 *Acta Phys. Sin.* **48** 1315 (in Chinese)

[3] Brandi O, Wuensche H J, Yang H *et al* 1998 *J. Crystal Growth* **189/190** 790

[4] Huang H Y, Lin W C, Lee W H *et al* 2000 *Appl. Phys. Lett.* **77** 2819

[5] Dassonneville S, Amorkrane A, Sieber B *et al* 2001 *J. Appl. Phys.* **89** 3736

[6] Shan W, Schmidt T J, Yang X H *et al* 1995 *Appl. Phys. Lett.* **66** 985

[7] Smith M, Chen G D, Lin J Y *et al* 1996 *J. Appl. Phys.* **79** 7001

[8] Chen G D, Smith M, Lin J Y *et al* 1996 *Appl. Phys. Lett.* **68** 2784

[9] Kane E O 1963 *Phys. Rev.* **131** 79

[10] Morgan T N 1965 *Phys. Rev.* **139** A343

[11] Schubert E F, Goepfert I D and Redwing J M 1997 *Appl. Phys. Lett.* **71** 3224