Efficient Acceptor Activation in $Al_xGa_{1-x}N$/GaN Doped Superlattices

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Abstract

Mg-doped superlattices consisting of uniformly doped $Al_xGa_{1-x}N$ and GaN layers are analyzed by Hall-effect measurements. Acceptor activation energies of 70 meV and 58 meV are obtained for superlattice structures with an Al mole fraction of $x = 0.10$ and 0.20 in the barrier layers, respectively. These energies are significantly lower than the activation energy measured for Mg-doped GaN thin films. At room temperature, the doped superlattices have free hole concentrations of 2×10^{18} cm^{-3} and 4×10^{18} cm^{-3} for $x = 0.10$ and 0.20, respectively. The increase in hole concentration with Al content of the superlattice is consistent with theory. The room temperature conductivity measured for the superlattice structures are 0.27 S/cm and 0.64 S/cm for an Al mole fraction of $x = 0.10$ and 0.20, respectively.

Introduction

Magnesium is the most common acceptor used in GaN. The large activation energy of Mg of 150 meV to 250 meV[1,2,3] results in a low acceptor ionization probability. Other acceptors such as Be and Ca also have large activation energies of 150 meV[4] and 169 meV[5], respectively. The low acceptor activation in *p*-type GaN results in large series resistances and high operating voltages, thereby adversely affecting the performance of electronic and optoelectronic devices.

Recently, it has been theoretically demonstrated that doped superlattice (SL) structures[6] increase the free hole concentration as compared to homogeneous thin-film *p*-type GaN. Doped superlattices are doped ternary compound semiconductor structures with a spatially modulated chemical composition. The modulation of the chemical composition leads to a variation of the valence band energy and to a reduction of the acceptor activation energy. Acceptors in the GaN layers of the superlattice must be ionized by thermal excitation. However, acceptors in the $Al_xGa_{1-x}N$ barriers are ionized more easily because these acceptors are close to the GaN valence band edge.

Experimental

In this publication, the electronic properties of $Al_xGa_{1-x}N$/GaN doped superlattice structures grown by MBE are analyzed. The superlattices consist of 20 periods of

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equally thick $Al_xGa_{1-x}N$ barriers (10 nm) and GaN wells (10 nm). The $Al_xGa_{1-x}N$ and GaN layers are uniformly doped with Mg at a level of $N_{Mg} \approx 10^{19}$ cm^{-3}. The Al mole fraction of the two different doped SLs are $x = 0.10$ and 0.20.

Hall-effect measurements were conducted on Mg-doped $Al_xGa_{1-x}N$/GaN superlattice samples. Photolithographically defined, 85 nm thick Ni contacts were deposited by electron-beam evaporation in the van der Pauw configuration. All samples display ohmic I-V characteristics. The samples were cooled in a Cryo Industries liquid nitrogen cryostat. Hall effect measurements, with a magnetic flux density of 0.5 T, were made between 150 - 400 K with 10 K intervals.

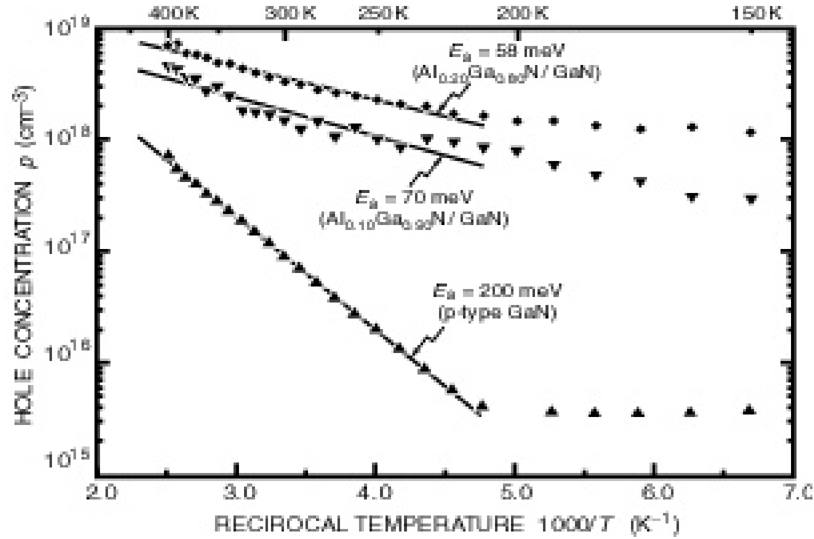

FIG. 1. Hole concentration verses reciprocal temperature for Mg-doped $Al_xGa_{1-x}N$/GaN superlattice samples with Al mole fraction in the barriers of $x = 0.10$ and 0.20. Also shown is a uniformly Mg-doped GaN thin-film sample with an acceptor activation energy of 200 meV.

Experimental results and discussion

Figure 1 shows the free hole concentration verses reciprocal temperature. The hole concentration displays an exponential dependence for temperatures in the range 220 - 400 K. The natural logarithm of the carrier concentration verses reciprocal temperature is fit with a least squares regression algorithm. The activation energy is determined using the relation

$$\ln p \quad \propto \quad -E_a / (k_B T) \tag{1}$$

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where E_a is the effective acceptor activation energy, k_B is Boltzmann's constant, and T is the absolute temperature. The measured activation energies for the superlattices with $x = 0.10$ and $x = 0.20$ are 58 meV and 70 meV, respectively. This result clearly shows that doped $Al_xGa_{1-x}N$/GaN superlattice structures have a lower activation energy than homogeneous Mg-doped GaN thin films.

At room temperature, the carrier concentration of the doped SL structures are 2×10^{18} cm^{-3} and 4×10^{18} cm^{-3} for an Al mole fraction $x = 0.10$ and $x = 0.20$, respectively. The sample with 20 % Al shows a factor of two larger carrier concentration than the sample with 10 % Al. Clearly, the free hole concentration increases with an increase of Al mole fraction in the barriers of the doped SLs. This increase is consistent with theory. It should be noted that most free carriers reside in the GaN layers. Assuming that the carrier concentration in the barriers is much smaller[6] than in the GaN well layers, the actual free carrier concentration the GaN well layers of the superlattice is 8×10^{18} cm^{-3} which is the highest free hole concentration ever achieved in GaN.

Katsuragawa and coworkers[7] showed that as the Al content is increased in homogeneous $Al_xGa_{1-x}N$ from $x = 0.00$ to $x = 0.33$ the hole concentration decreases monotonically. Tanaka and coworkers[8] reported that for Mg-doped GaN to $Al_{0.08}GaN_{0.92}N$, the activation energy increases from 157 meV to 192 meV. In contrast, doped superlattice structures have smaller activation energies and larger carrier concentrations as the mole fraction of Al is increased in the superlattice barriers.

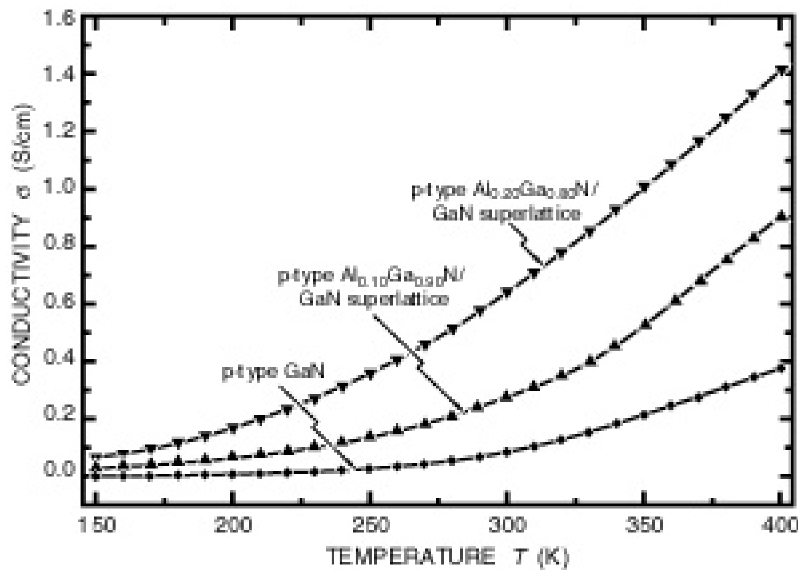

FIG. 2. Conductivity verses temperature for *p*-type $Al_xGa_{1-x}N$/GaN doped superlattices and homogeneous *p*-type GaN.

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The conductivity verses temperature for the two SL structures are depicted in Figure 2. The room-temperature conductivity is 0.27 S/cm and 0.64 S/cm for the superlattice with an Al mole fraction of $x = 0.10$ and 0.20, respectively. At room temperature the conductivity for the SL with 20 % Al has a conductivity almost a factor of three greater than for the SL with 10 % Al. Note that the results shown in Figure 2 are the highest *p*-type conductivities achieved in a III-nitride semiconductor containing aluminum.

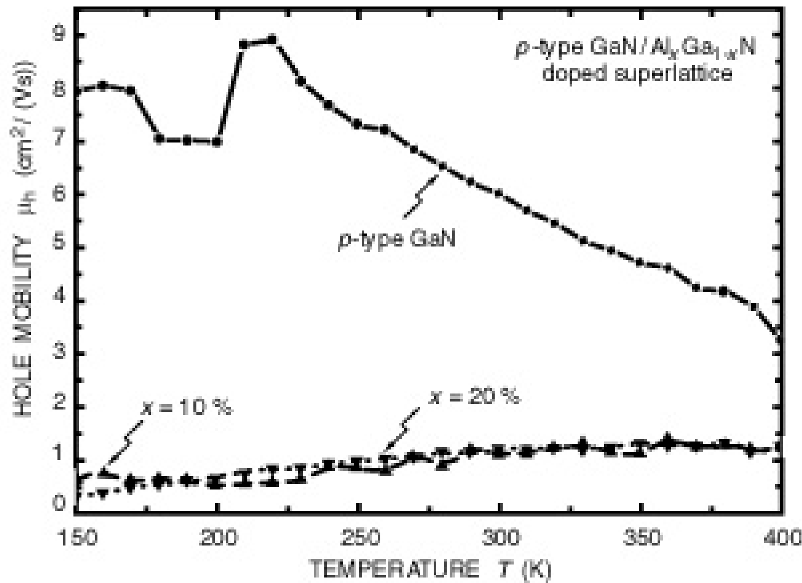

FIG. 3. Mobility verses temperature for *p*-type $Al_xGa_{1-x}N$/GaN doped superlattices and homogeneous *p*-type GaN.

Figure 3 depicts the mobility verses temperature for the doped superlattice samples. Note, that for an increase in Al content, the mobility does not change. The mobilities of the doped SL structures increase monotonically with temperature by more than a factor of three in the temperature range 150 - 400 K. This is in contrast to *p*-type GaN which exhibits a decrease in mobility as the temperature increases beyond 200 K. Due to the temperature dependence of the mobility, conductivity data without carrier concentrations[9] will result in an overestimation of the acceptor activation energy.

We have calculated the carrier concentration as a function of temperature for an $Al_xGa_{1-x}N$/GaN doped superlattice with x varied between $x = 0.00$ and $x = 0.30$. The thicknesses of the GaN and $Al_xGa_{1-x}N$ regions are both 10 nm. A uniform doping profile of $N_A = 1 \times 10^{18}$ cm^{-3} and an acceptor activation energy of $E_a = 200$ meV in the GaN and the $Al_xGa_{1-x}N$ is assumed. Using the parameters $\varepsilon_r = 9.0 - 0.5\,x$ for the relative

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permittivity[10] and $m_p{*} = 0.8\ m_0$ for the effective hole mass[11], the hydrogenic model does not predict a significant deepening of the acceptor level in $Al_xGa_{1-x}N$ for $x \leq 0.20$. This is consistent with the experimental results of Katsuragawa et al.[7] who showed that the activation energy does not change markedly with the Al content. To determine the carrier concentration, the arithmetic average of the position dependent carrier concentration over one period of the superlattice is computed for a given Al content and temperature.

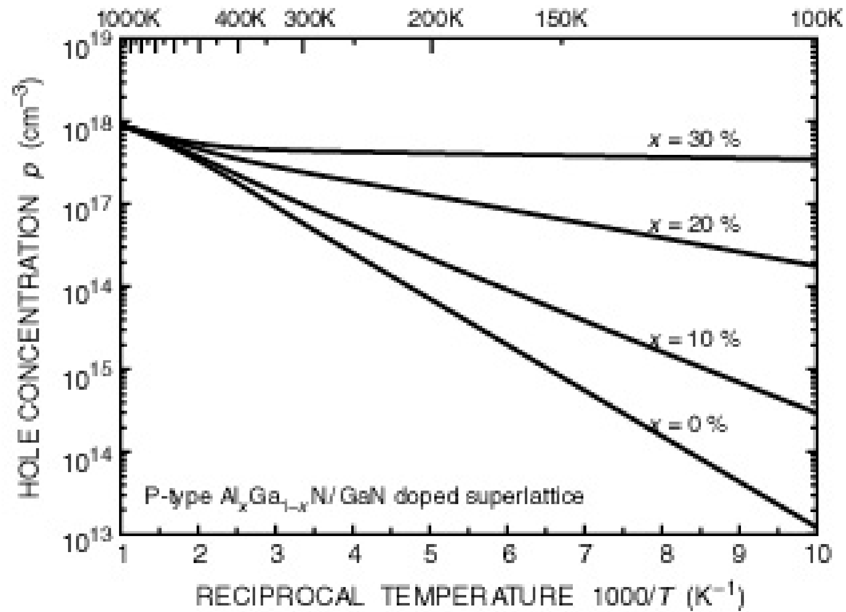

FIG. 4. Calculated hole concentration verses reciprocal temperature for *p*-type $Al_xGa_{1-x}N$/GaN doped superlattices with Al mole fractions of $x = 0.00$, 0.10, 0.20, and 0.30.

Figure 4 depicts the calculated carrier concentration verses $1/T$ for four doped SLs with different Al content in the $Al_xGa_{1-x}N$ barriers. Examination of the four curves shows that the carrier concentration increases with an increase in Al content in the barriers. Note, that in the freeze-out regime, the slope of each curve represents the effective activation energy of the acceptor, which decreases with increasing Al content in the barriers. Our experimental results shown in Figure 1 are consistent with the results of the theoretical model.

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Conclusions

In conclusion, the electronic properties of Mg-doped superlattices consisting of uniformly doped $Al_xGa_{1-x}N$ and GaN layers are analyzed by Hall-effect measurements. Acceptor activation energies of 70 meV and 58 meV are reported for superlattice structures with an Al mole fraction of $x = 0.10$ and 0.20 in the barrier layers, respectively. These energies are substantially lower than the activation energy measured for Mg-doped GaN thin films. At room temperature, the doped superlattices have free hole concentrations of $2 \times 10^{18}\ cm^{-3}$ and $4 \times 10^{18}\ cm^{-3}$ for $x = 0.10$ and 0.20, respectively. The increase in hole concentration with Al content of the superlattice is consistent with theory. The room temperature conductivity measured for the superlattice structures are 0.27 S/cm and 0.64 S/cm for an Al mole fraction of $x = 0.10$ and 0.20, respectively.

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[10] We use $\varepsilon_r = 9.0$ and $\varepsilon_r = 8.5$ for the relative dielectric constant for GaN and AlN, respectively. These values are compiled in Reference 1.

[11] The experimental effective hole mass in $Al_xGa_{1-x}N$ is unknown at this time. Although, Katsuragawa et al. in Reference 7 reported no significant change in the activation energy of Mg in $Al_xGa_{1-x}N$ indicating no significant change in the hole mass. See, for instance, Gil, *Group III Nitride Semiconductor Compounds* (Clarendon Press, Oxford, 1998)

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