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GaN HBTs are promising for microwave power applications but face numerous technology barriers. In this project, we are addressing the enhancement of the hole concentration in p-type GaN by piezoelectric effects and/or the use of superlattices. We are currently assessing the activity of Mg-doped GaN on sapphire and lithium gallate as grown by MBE. In addition, we are modeling these effects to optimize the hole concentration in realistic HBT structures.

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HBT Progress Report

Experimental

Much of the effort has been focussed on the training of a new graduate student, Gon Namkoong, and the growth of Mg-doped GaN on sapphire and LGO. The student has been completely trained and can independently characterize material. A summary of the p-type doping issues and status are given below.

Mg on LGO:

Mg-doped GaN on LGO has been attempted. Mg doping may promote peeling of the GaN film from the substrate. We have observed peeling with some batches of material and for thicker GaN films. To date, 1 x 10^{17} cm^{-3} hole concentration has been achieved on GaN on LGO. We do not feel we have exhausted the growth condition space for GaN:Mg on sapphire so we will continue this effort.

Mg on Sapphire:

To date, 2x10^{17} cm^{-3} hole concentration at ~9 cm ^{2}/Vsec mobility has been achieved on sapphire. Both N-rich and Ga-rich have been investigated. As with GaN on LGO, we do not feel we have exhausted our possibilies for growth conditions. While we need to obtain a baseline for our MBE system for Mg doping in GaN on sapphire, the optimization of growth conditions requires more effort.

Anomalous p-type doping:

Three separate samples have shown results indicating hole concentrations as high as 1x 10^{19} cm^{-2}. Two of these samples were undoped GaN grown at a moderately low temperature of 680 C. The third sample was an AlGaN/GaN FET structure. Positive and negative ion SIMs analysis (to cover the full periodic table) revealed no contamination. other than fluorine and chlorine. The concentration of these impurities was estimated at two orders of magnitude lower than the reported hole concentration. Possible explanations include Hall measurements of mixed carrier conduction, or activation energy lowering from increased disorder. Other Si doped samples grown under lower temperatures have indicated n-type conduction at room temperature, high "acceptor-like" PL behavior as a function of temperature. The energy transitions attributed to these "acceptor-like" transitions are considerably lower (~0.2 eV) than those attributed to Mg acceptor levels (0.22-0.26 eV). As of yet, no p-type conduction has been achieved with this "native defect".

Al:Mg doping:

Al:Mg "codoping" has been attempted. It is known in GaAs that the presence of Al improves the sticking coefficient of Mg by several orders of magnitude. Also, since the Al-O bond is stronger that the Mg-O bond by a large amount (511 KJ/mole verses 363 KJ/mole) it is expected that Al will help purify the Mg by gettering the oxygen. It is unclear as to what effect the Al-O species will have on the material. To date, only high resistivity material has been achieved with this approach.

InGaN:GaN MQW

Since InGaN has a lower band gap than GaN, it may result in a lower activation energy for Mg. One set of Mg doped MQW structures has been grown. These structures resulted in high resistivity material. This is fairly promising, since InN generally is always heavily n-type.

Future Work: We will continue exploring the growth conditions for p-type GaN on LGO, sapphire, and GaN on sapphire (in conjunction with TRW). In addition, the relationship between hole concentrations and multi-quantum well properties will be examined. LGO promises to be a particularly good substrate for low temperature growth and InGaN growth. In addition, we will complement the efforts of the theoretical analysis described through appropriate experiments.

Finally, we are purchasing an EPI rf plasma source to replace our Oxford source. Other researchers have had real success in improving the electrical properties of nitrides with this source.

Theoretical Effort

One of the stated goals of the HBT program is to determine ways in which the p-type doping concentration of GaN can be enhanced. During the past period of performance on this project we have primarily focused on two different approaches. These are: 1) usage of the piezoelectric effect in GaN/AlGaN heterostructures to alter the free carrier concentration and local electric field strength, and 2) examine how GaN/AlGaN or GaN/InGaN superlattice structures can be utilized to alter the activation energy of the dopants to increase the hole carrier concentration. Below we summarize our progress in these two studies.

We have spent considerable effort in first understanding and formulating the action of the piezoelectric effect in a heterostructure system. The basic concept of utilizing the piezoelectrically induced field to alter the electrical properties of a material can be understood as follows. A heterostructure comprised of an overlayer of AlGaN on GaN can be formed which is strained due to the inherent lattice mismatch of the constituent layers. At some critical thickness of the overlayer, it becomes energetically favorable for the system to form dislocations to relieve the strain. For the AlGaN/GaN system, the critical thickness is mostly a function of the Al composition of the overlayer. For example, at an Al composition of 20% the critical thickness of the overlayer AlGaN is 30 nm. Therefore, layers thicker than 30nm will relax the strain through the formation of dislocations. However, if layers thinner than 30nm are made, the layer remains strained. A general polarization field is developed due to the strain since the material does not have inversion symmetry. This is true for either the zincblende or wurtzite phases. In this investigation we have focused on the wurtzite phase. The polarization is proportional to the strain. Since the strain is related to the composition of the overlayer, the polarization field can be readily engineered. The polarization field can then be utilized to alter the local field strength within the overlayer and subsequently at the

heterointerface. We have analyzed how the polarization field can be utilized to alter the local field profile to alter the impact ionization rate. The results of this analysis have been published in Applied Physics Letters, and a copy of that paper is enclosed.

Depending upon how the interface is terminated, the polarization field within the overlayer can produce either positive or negative charge accumulation at the surface. In this way, the polarization field due to the strained overlayer can be used to change the surface condition, inducing positive charge for instance without adding additional acceptors. During the course of this work, we have developed all of the theoretical modeling tools necessary to determine the polarization field and to estimate the carrier concentration that can be induced at the heterointerface.

The second general approach for enhancing the p-type conductivity of GaN that we have considered to date in this program is to utilize a doped GaN/AlGaN or GaN/InGaN superlattice. In this concept, we envision that by doping an AlGaN layer with Mg within a superlattice, that the Mg can be more readily ionized producing a higher hole concentration. The general idea can be understood as follows. First we assume that the acceptor level is roughly at the same energy within either the GaN or AlGaN layers with respect to the valence band edge. A GaN/AlGaN superlattice is formed in which the AlGaN layers are doped p-type with Mg. Owing to the valence band edge discontinuity, the GaN valence band lies relatively close to the impurity level in the surrounding AlGaN layers. Therefore, the acceptor level can become more readily ionized in the superlattice than in bulk GaN material. We have developed theoretical tools for designing test superlattice structures. In addition, we have grown InGaN/GaN superlattice structures. However, these structures were all n-type. Future work will involve growing AlGaN/GaN superlattices with Mg doped AlGaN layers.

The effect of strain-induced polarization fields on impact ionization in a multiquantum-well structure

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We present a mechanism for enhancing the electron impact ionization rate based on the strain-induced polarization fields in a strained multiquantum-well system. To illustrate the concept, the electron ionization rate is calculated for a strained GaN and $Al_{0.3}Ga_{0.7}N$ multiquantum-well device. The presence of the polarization fields within the $Al_{0.3}Ga_{0.7}N$ layers provides an additional mechanism for carrier heating to the conduction band edge discontinuity of earlier simple multiquantum-well avalanche photodiode designs. It is found that the ionization rate is substantially enhanced over both its bulk GaN value and that for an unstrained multiquantum-well structure.
 [S0003-6951(98)01445-4]

The prediction[1] and observation[2] of piezoelectrically induced strain polarization fields in strained semiconductor systems has introduced an engineering degree of freedom in semiconductor device design. In lattice mismatched heterostructure systems with sufficiently thin layers, the lattice mismatch is accommodated by internal strains rather than by the formation of misfit dislocations. These strains induce polarization fields that can be used to alter the carrier concentration in the immediate vicinity of a heterostructure layer by changing the local electric field and conduction band profile. One important application of these fields is to accumulate large free carrier densities at the heterointerface without introducing modulation doping. Recent experimental measurements[3,4] have indicated that sizable carrier concentration densities can be induced through the action of the piezoelectric field at strained layer interfaces. Very high two-dimensional carrier concentrations have been reported.[5–7] Based on this effect, a type of heterostructure field effect transistor has been suggested.[8]

The action of the strain-induced polarization fields can be further exploited to alter the optoelectronic properties of a multiquantum-well (MQW) system.[9] Through judicious choice of the design parameters, the average electric field within the active region of an optical absorber can be influenced, resulting in observable shifts in the photoluminescence signal.[9]

In this letter, we present a method of exploiting the strain-induced polarization fields to produce an enhancement in the carrier impact ionization rate coefficient. A strained multiquantum-well system is used to form the intrinsic region of an avalanche photodiode. The basic structure is sketched in Fig. 1(a). To illustrate the concept, we select GaN and $Al_{0.3}Ga_{0.7}N$ as the constituent materials but it should be noted that any other strained materials system, such as InGaAs–GaAs, will suffice. As shown in the diagram, the intrinsic region is comprised of thin layers of strained $Al_{0.3}Ga_{0.7}N$ alternating with GaN. The structure is very similar to earlier multiquantum-well avalanche photodiode (APD) designs[10,11] except that the layers are now strained. As in the earlier multiquantum-well APD designs, the layers are unintentionally doped, and made as close to intrinsic material as possible. The strained layers produce polarization fields as discussed above. The presence of the strained polarization fields, induced in both the $Al_{0.3}Ga_{0.7}N$ and GaN layers, results in modified field, potential and conduction band profiles. Through a proper selection of the strain condition and the polarization charge, the electric field strength can be selected to accelerate the electrons within the $Al_{0.3}Ga_{0.7}N$ layer prior to their injection into the narrower energy gap GaN layer. As in earlier multiquantum-well APD structures, the electron ionization rate can be enhanced over its bulk value.[12,13] However, in the strained multiquantum-well structure, the carriers are locally heated by both the strain-induced polarization field and the conduction band edge discontinuity. As shown below, the additional action of the polarization fields substantially enhances the carrier ionization rate.

To demonstrate the validity of this concept, we calculate the electron impact ionization rate using the simple theory of impact ionization in the multiquantum-well structures of Brennan *et al.*[14] In that theory, the authors expand the periodic square well potential of the multiquantum well in a Fourier series. In the present case, the polarization fields vary with the periodicity of the superlattice and thus produce an additional periodic component to the potential and electric field. The calculation is made as follows.

The magnitudes of the polarization fields in the GaN and $Al_{0.3}Ga_{0.7}N$ layers strained along [0001] crystallographic direction are determined from[15]

$$P_{1,2} = \pm 2\left(e_{31} - e_{33}\frac{c_{31}}{c_{33}}\right)u_{xx}, \tag{1}$$

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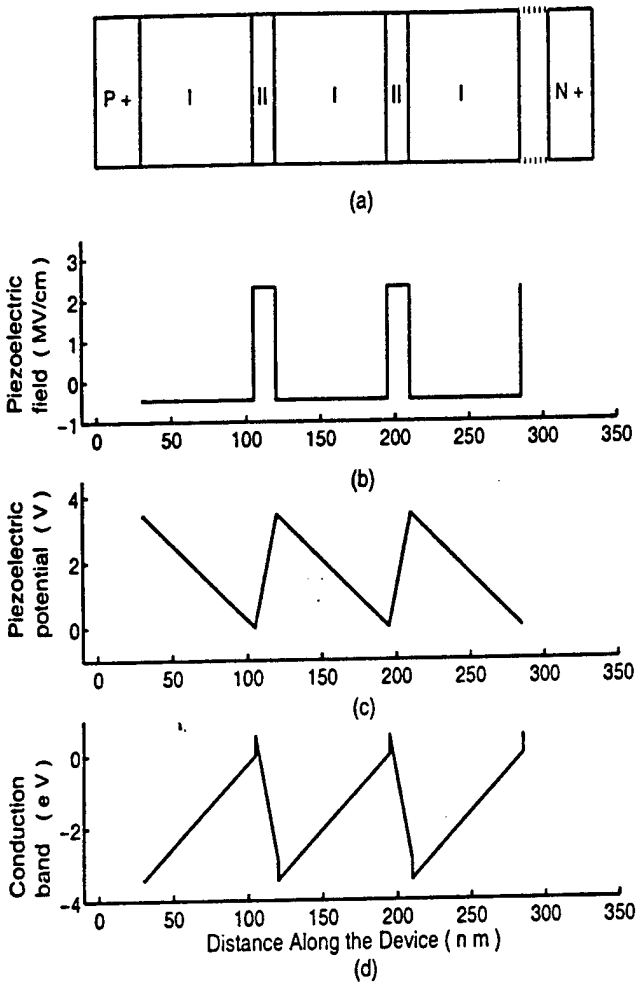

FIG. 1. Sketch of the (a) overall avalanche photodiode structure, where the strained wide band gap semiconductor layer is labeled II and the narrow band gap layer is labeled I; (b) resulting electric field profile, (c) potential profile, and (d) conduction band edge for an example 75–15 nm width strained multiquantum-well device. Note that the $n+$ and $p+$ layers are included only for illustration and their effect is neglected in the field, potential and conduction band sketches.

where 1 and 2, + and − apply to $Al_{0.3}Ga_{0.7}N$ and GaN, respectively. Using recent values for the piezoelectric tensor components, e_{31} and e_{33},[16] and elastic constants, c_{31} and c_{33},[17] for GaN and AlN, and linearly interpolating to obtain the $Al_{0.3}Ga_{0.7}N$ values, P_1 and P_2 are, -1.13×10^{-6} C/cm^2 and 1.03×10^{-6} C/cm^2, respectively. For a superlattice, the fields are given as[18]

$$F_1=\frac{P_2-P_1}{\epsilon_o\left(\epsilon_1+\epsilon_2\frac{L_1}{L_2}\right)}, \tag{2}$$

$$F_2=-F_1\frac{L_1}{L_2}, \tag{3}$$

where ϵ_1 and ϵ_2 are the relative dielectric constants, 8.78 and 8.9, for $Al_{0.3}Ga_{0.7}N$ and GaN, respectively. L_1 and L_2 are the layer widths. From Ref. 18 the critical thickness of the $Al_{0.3}Ga_{0.7}N$ can be estimated to be about 15 nm. Assuming that the GaN layer is five times the width of the $Al_{0.3}Ga_{0.7}N$ layer, the fields, F_1 and F_2, are calculated to be 2.3 and −.46 MV/cm, respectively. Finally, the conduction band edge discontinuity, ΔE_c, is taken as 0.53 eV.[19] The calculated electric field, potential and conduction band profile for this structure is sketched in Fig. 1.

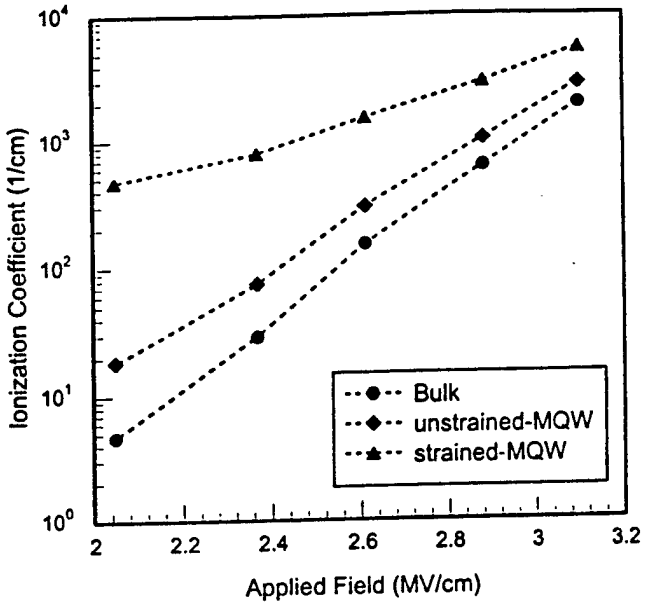

FIG. 2. Calculated electron impact ionization rate coefficient as a function of the overall applied electric field magnitude for three cases, bulk GaN, unstrained, simple GaN–$Al_{0.3}Ga_{0.7}N$ multiquantum well, and strained GaN–$Al_{0.3}Ga_{0.7}N$ multiquantum well. Notice that the ionization rate is substantially higher in the strained system than in either the unstrained or bulk material

The electron impact ionization rate coefficient is calculated based on the field and potential profile shown in Fig. 1 using a modified version of Shockley's lucky electron theory.[14] The multiquantum-well potential is expanded in a complete Fourier series over the full superlattice period. The polarization fields in the layers are superimposed onto the field arising from the superlattice potential, $F(z)$.[14] The ionization rate can then be determined numerically using expressions similar to Eq. (5) in Ref. 14 as

$$\alpha_z=\frac{1}{L}\frac{e}{E_{\rm th}}\int_0^{L_1}F_o e^{-C/[F_o+F_1-\partial V_z/\partial z]}dz + \frac{1}{L}\frac{e}{E_{\rm th}}\int_{L_1}^{L_1+L_2}F_o e^{-C/[F_o+F_2-\partial V_z/\partial z]}dz, \tag{4}$$

where F_o is the constant overall field, F_1 and F_2 are the polarization fields in the AlGaN and GaN layers, respectively, V_z is the superlattice potential, $E_{\rm th}$ the threshold energy, and C a factor that is obtained by fitting the calculation to the bulk ionization rate.[14] The electron ionization coefficients used for the wurtzite phase of bulk GaN to determine C are taken from Kolnik *et al.*[20] and hold for a lattice temperature of 300 K.

The results calculated for α_z (Fig. 2) indicate that the electron ionization rate is strongly enhanced by the combined action of the polarization fields and the conduction band edge discontinuity. As can readily be seen from Fig. 2, the ionization rate in the strained multiquantum-well structure is very much larger than that of either bulk GaN or an equivalent, but unstrained, GaN–$Al_{0.3}Ga_{0.7}N$ multiquantum-well device. Notice that as the overall bias field increases, the

ionization rates in both multiquantum-well structures approach the bulk rate. This is as expected since the action of the multiquantum-well potential becomes less important as the overall bias field increases. The relative importance of the piezoelectric field and the conduction band edge discontinuity on the impact ionization coefficient can be understood from an inspection of Fig. 2 as well. Note that at a field of 2.1 MV/cm, the ionization coefficient within the unstrained MQW device is about two times larger than in bulk GaN. The enhancement of the ionization coefficient in the unstrained MQW arises solely from the action of the discontinuity. The ionization coefficient is much larger in the strained MQW device, about two orders of magnitude larger than bulk GaN, for the same applied field due to the further action of the piezoelectric field.

The polarization fields will also heat the holes. It is likely then that the hole ionization rate will also be enhanced. However, the larger mass and relaxation rate of the holes should limit the enhancement to below that of the electrons. The present formulation is too simplified to properly reflect the differences in the dynamics of the electrons and holes in the structure. Therefore, a future work, including a complete, full band Monte Carlo calculation[21] will address this issue and determine the degree to which the strained superlattice can alter the electron to hole ionization rates ratio.

In conclusion, we have presented a mechanism, based on the strain-induced polarization fields in a strained multiquantum-well structure, to enhance the electron ionization rate. The polarization fields within the barrier layers combine with the conduction band edge discontinuity to greatly heat the electrons, resulting in a substantial increase in the ionization rate. The particular advantage of this approach is that the strain-induced fields can be readily controlled by adjusting the layer widths through the growth process. This is in contrast to the doped quantum well and barrier devices[22–24] where the electric fields within the barrier regions are produced by highly doping $p+$ and $n+$ layers to form minijunctions. It has been recognized[25] that control of the doping concentrations to the degree required for complete depletion of the layers is exceedingly difficult. The present strained multiquantum-well device overcomes this limitation yet still provides very high built-in electric fields within the barrier layers. The degree to which the present structure will alter the electron to hole ionization rates ratio is presently unknown. However a complete, full band Monte Carlo calculation will be performed to determine the electron to hole ionization rates ratio in the strained multiquantum-well device.

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[1] D. L. Smith, Solid State Commun. **57**, 919 (1986).
[2] E. A. Caridi, T. Y. Chang, K. W. Goossen, and L. F. Eastman, Appl. Phys. Lett. **56**, 659 (1990).
[3] E. S. Snow, B. V. Shanabrook, and D. Gammon, Appl. Phys. Lett. **56**, 758 (1990).
[4] X. Li, K. F. Longenbach, and W. I. Wang, Appl. Phys. Lett. **60**, 1513 (1992).
[5] R. Gaska, J. W. Yang, A. D. Bykhovski, M. S. Shur, V. V. Kaminski, and S. M. Soloviov, Appl. Phys. Lett. **72**, 64 (1998).
[6] P. M. Asbeck, E. T. Yu, S. S. Lau, G. J. Sullivan, J. Van Hove, and J. Redwing, Electron. Lett. **33**, 1230 (1997).
[7] E. T. Yu, G. J. Sullivan, P. M. Asbeck, C. D. Wang, D. Qiao, and S. S. Lau, Appl. Phys. Lett. **71**, 2794 (1997).
[8] T. F. Kuech, R. T. Collins, D. L. Smith, and C. Mailhiot, J. Appl. Phys. **67**, 2650 (1990).
[9] J. L. Sanchez-Rojas, A. Sacedon, F. Calle, E. Calleja, and E. Muñoz, Appl. Phys. Lett. **65**, 2214 (1994).
[10] R. Chin, N. Holonyak, Jr., G. E. Stillman, J. Y. Tang, and K. Hess, Electron. Lett. **16**, 467 (1980).
[11] F. Capasso, W. T. Tsang, A. L. Hutchinson, and G. F. Williams, Appl. Phys. Lett. **40**, 38 (1982).
[12] T. Kagawa, Y. Kawamura, H. Asai, M. Naganuma, and O. Mikami, Appl. Phys. Lett. **55**, 993 (1989).
[13] T. Kagawa, H. Asai, and Y. Kawamura, IEEE Photonics Technol. Lett. **3**, 815 (1991).
[14] K. Brennan, K. Hess, and F. Capasso, Appl. Phys. Lett. **50**, 1897 (1987).
[15] R. Gaska, J. W. Yang, A. Osinsky, A. D. Bykhovski, and M. S. Shur, Appl. Phys. Lett. **71**, 3673 (1997).
[16] F. Bernardini, V. Fiorentini, and D. Vanderbilt, Phys. Rev. B **56**, R10024 (1997).
[17] K. Kim, W. R. L. Lambrecht, and B. Segall, Phys. Rev. B **50**, 1502 (1994).
[18] A. D. Bykhovski, B. L. Gelmont, and M. S. Shur, J. Appl. Phys. **81**, 6332 (1997).
[19] S. N. Mohammad, A. A. Salvador, and H. Morkoç, Proc. IEEE **83**, 1306 (1995).
[20] J. Kolnik, I. H. Oguzman, K. F. Brennan, R. Wang, and P. P. Ruden, J. Appl. Phys. **81**, 726 (1997).
[21] K. F. Brennan and Y. Wang, IEEE Trans. Electron Devices **35**, 634 (1988).
[22] K. Brennan, IEEE Trans. Electron Devices **ED-34**, 782 (1987).
[23] K. Brennan, IEEE J. Quantum Electron. **QE-22**, 1999 (1986).
[24] H. M. Menkara, B. K. Wagner, and C. J. Summers, Appl. Phys. Lett. **66**, 1764 (1995).
[25] H. M. Menkara, B. K. Wagner, and C. J. Summers, Opt. Mater. **6**, 103 (1996).