The Franz–Keldysh effect in shocked GaN:Mg

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The band gap of uniaxially strained semi-insulating GaN:Mg has been examined using time-resolved optical transmission measurements in shock-wave experiments. For longitudinal stresses between 2.9 and 4.6 GPa, the absorption edge broadened significantly. Such a broadening is consistent with the presence of large piezoelectric fields (Franz–Keldysh effect) generated due to shock compression. For stresses greater than 4.6 GPa, however, the absorption edge remained relatively sharp. The sharp absorption onset suggests the presence of free charge carriers that screen the piezoelectric field, thereby suppressing the Franz–Keldysh effect. These observations indicate that electrical breakdown occurs at a field of 1 MV/cm. One possible mechanism that could result in free carriers is the dissociation of Mg–H complexes under the very high piezoelectric fields. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1563837]

Efficient p-type doping of GaN is important for the development of wide-band-gap electronic and optoelectronic devices. For III–V nitrides, the most commonly used acceptor dopant is Mg. However, due to compensation by background n-type defects and the passivation of Mg by hydrogen, GaN:Mg epilayers grown by metalorganic chemical vapor deposition (MOCVD) are semi-insulating. Amano *et al.*[1] found that GaN:Mg can be converted into p-type GaN by a low-energy electron-beam irradiation treatment. Later, Nakamura *et al.*[2] showed that thermal annealing could also activate the Mg acceptors. Several experiments[3–5] have demonstrated that the injection of minority-carrier electrons greatly enhances the activation process. More recently, several groups[6–10] reported that enhanced Mg doping efficiency could be realized in AlGaN/GaN superlattices. An average hole concentration of over 2.5×10^{18} cm^{-3} at room temperature was measured,[10] more than ten times that obtained in bulk GaN layers. One possible explanation for this high hole concentration is that piezoelectric (PZE) fields increase the electrical activity of the relatively deep Mg acceptors in the superlattices.

While the activation of Mg acceptors is of technological importance, the role of PZE fields on the activation process is difficult to ascertain. To address this question, we investigated the time-resolved optical absorption properties of GaN:Mg films under shock loading. Due to the PZE effect, a large electric field should be produced along the c-axis during shock compression. Hence, shock compression is an excellent experimental probe to study the activation of hydrogen-passivated Mg due to PZE fields.

Samples used in this study were 4-μm-thick GaN:Mg epilayers grown on a c-cut, 420-μm-thick sapphire substrate by MOCVD. The layers were doped with $\sim10^{20}$ Mg atoms/cm^3 and were semi-insulating as grown. Light from a xenon flashlamp passed through the impactor (c-cut sapphire), sample (with sapphire substrate facing the impactor), and buffer back window (c-cut sapphire).[11] The light was collected by a fused silica lens and focused into an optical fiber. The transmitted light was spectrally dispersed by a spectrometer and temporally dispersed by an electronic streak camera. The output was recorded on a CCD detector as a series of transmission spectra, each separated in time by 20 ns. The shock waves were generated by projectile impact, where the projectile and the impactor were accelerated to the desired velocity using a light-gas gun. The applied stress along the c-axis ranged from 2.89 to 13.7 GPa. The peak stress reached in the GaN layer was maintained for approximately 130–270 ns, depending on the size of each sample. All experimental data were collected within this time window. Details of the experimental setup may be seen in Refs. 11 and 12.

The experimentally measured absorption spectra of the GaN:Mg samples before (dashed lines) and after (solid lines) shock compression, for different peak stresses, are shown in Fig. 1. We took the shocked absorption spectrum to be the one recorded 120 ns after the shock wave arrives at the GaN layer. The absorption coefficients were determined using the expression

$$\alpha=\ln\left(\frac{I_0-I_b}{I-I_b}\right)/d, \quad (1)$$

where I is the transmitted intensity of the GaN:Mg sample recorded during the shock, I_0 is the intensity transmitted through a sapphire reference sample, I_b is the background intensity recorded with the streak camera shutter closed, and d is the thickness of the GaN:Mg film. Only the tail region of the band edge absorption ($\alpha<0.5\times10^4$ cm^{-1}) could be observed, due to the thickness of the GaN epilayer. The flat top of each spectrum on the high energy side is an artifact caused by the limited dynamic range of the recording system. The band-gap threshold, indicated by the arrows in Fig. 1, was defined as the energy at which the first derivative of the

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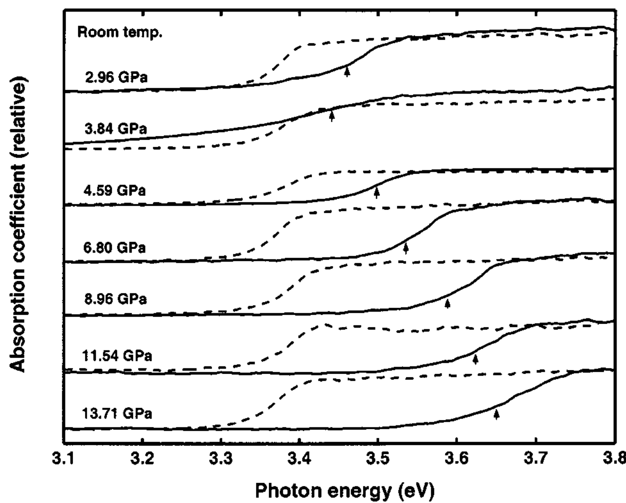

FIG. 1. Absorption spectra of GaN:Mg thin films before (dotted lines) and after (solid lines) shock compression to different longitudinal stresses. Arrows indicate the band-gap threshold of shocked GaN:Mg.

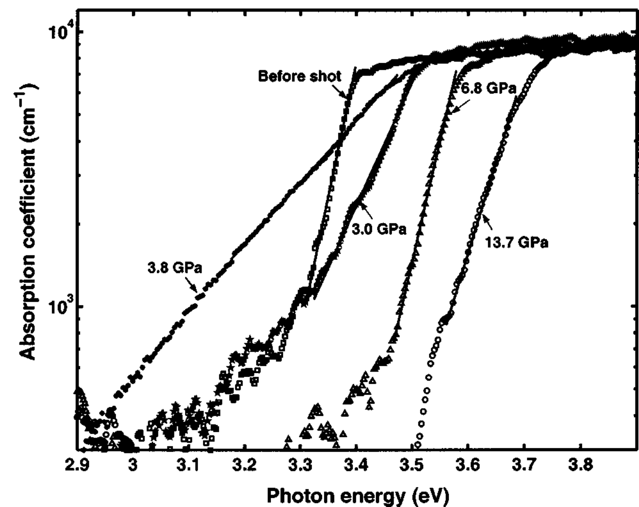

FIG. 2. Absorption coefficient of GaN:Mg samples as a function of photon energy before and after shock compression. The solid lines are linear fits to the data.

absorption spectrum reaches a maximum. From Fig. 1, it can be seen that the band-gap threshold shifts to higher energy with increasing stress (except the one at 3.84 GPa). The band-gap shift is approximately 25 meV/GPa, in good agreement with the shift measured in undoped ($n \sim 10^{17}$ cm^{-3}) GaN.[12]

In the presence of an electric field, the optical absorption edge of direct band-to-band optical transitions in semiconductors broadens and shifts towards lower energy (Franz–Keldysh effect). At photon energies below the zero-field band gap, the absorption coefficient assumes an asymptotic form of the Franz–Keldysh shape[13]

$$\alpha \sim \exp\left(\frac{-C_0|E-E_0|^{1.5}}{F}\right), \tag{2}$$

where E is the photon energy, F is the electric field strength, and C_0 and E_0 are constants. However, Dow *et al.*[14] and Blossey[15] pointed out that exciton effects must be taken into account, leading to an optical-absorption coefficient given by

$$\alpha \sim \exp\left(\frac{-C_0'|E-E_0'|}{F}\right), \tag{3}$$

where C_0' and E_0' are constants. In order to determine which model is more applicable, the experimental absorption coefficient α was plotted as a function of photon energy E in a logarithmic scale (Fig. 2). The linear relationship of $\ln \alpha$ versus E in Fig. 2 shows that the model of Dow and Blossey [Eq. (3)] provides a good description of the absorption coefficient.

The slope of $\ln \alpha$ versus E before and after shock compression is denoted S_{bef} and S_{aft}, respectively. S_{bef} varied somewhat ($\pm 8\%$) from sample to sample. The spread in values may be due to variations in film thickness, post-growth cooling rates, and defect density across the wafer. These factors can affect the in-plane biaxial strain or hydrostatic strain[16] retained by the film after deposition, resulting in different band-gap shifts and PZE fields. In order to eliminate these effects, the slope ratio $S_{\mathrm{aft}}/S_{\mathrm{bef}}$, as shown in Fig. 3, was used to characterize the broadening of the band-gap absorption caused by shock compression. The slope ratio exhibits different behavior for $\sigma_{33}<4.6$ GPa (stage I) and $\sigma_{33}>4.6$ GPa (stage II). As discussed later, this behavior can be explained by the screening of PZE fields.

Below the Hugoniot elastic limit of the material, plane-wave shock loading will give rise to uniaxial strain, $\epsilon_{11}=\epsilon_{22}=0$ and $\epsilon_{33}=\sigma_{33}/C_{33}$, where ϵ_{ij} and σ_{ij} are components of the strain and stress tensors, respectively, and C_{ij} are the elastic constants. Under uniaxial strain, the magnitude of the PZE field produced along the c-axis is given by

$$F=\frac{e_{33}\sigma_{33}}{\epsilon\epsilon_0 C_{33}}, \tag{4}$$

where e_{33} is a piezoelectric constant, ϵ is the c-axis static dielectric constant, and ϵ_0 is the permittivity of free space. Alternatively, the field may be expressed as

$$F=\frac{(2d_{31}C_{13}+d_{33}C_{33})\sigma_{33}}{\epsilon\epsilon_0 C_{33}}, \tag{5}$$

where d_{ij} are the piezoelectric constants that relate polarization to stress. From these expressions, it is apparent that the strain-induced PZE field increases with stress σ_{33}. The results for undoped GaN (dashed line in Fig. 3), which show a broadening of the absorption threshold that increases monotonically with stress, are in qualitative agreement with Eq. (4). However, the present results for semi-insulating GaN:Mg (solid line in Fig. 3) are consistent with an abrupt *decrease* of the electric field at a stress of 4.6 GPa. This phenomenon indicates a strong screening of the PZE field in stage II.

According to Eq. (4), the PZE field produced at 4.6 GPa is 0.94 MV/cm using the following parameters: $C_{13}=106$ GPa,[17] $C_{33}=398$ GPa,[17] $\epsilon=10.1$,[18] and the calculated value $e_{33}=0.73$ C/m^2.[19] From Eq. (5), the field is 1.28 MV/cm, using the experimental values $d_{31}=-1.7\times10^{-10}$ cm/V[20] and $d_{33}=3.4\times10^{-10}$ cm/V.[21] At such a high PZE field, the Mg–H complexes may dissociate, resulting in free holes from the activated Mg acceptors. These holes would then screen the PZE field. It should be noted that wurtzite GaN does not have any structural transition at pressures less than 37 GPa.[22] Furthermore, continuum measurements on

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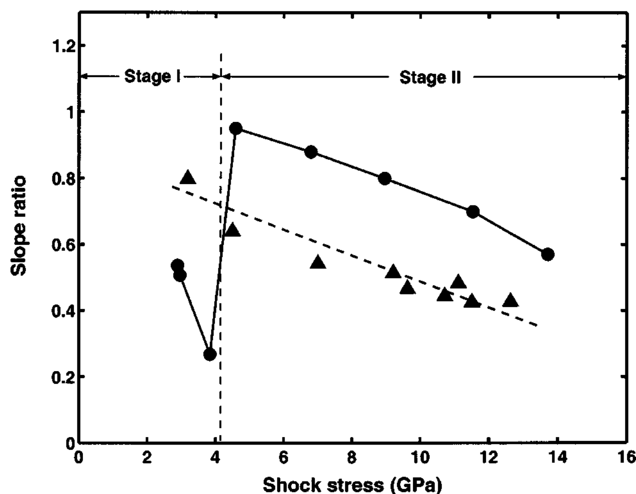

FIG. 3. Measured slope ratio S_{aft}/S_{bef} as a function of shock stresses. Circles denote results from semi-insulating GaN:Mg, while triangles are from undoped (n-type) GaN. The slope ratios are inversely proportional to the broadening of the band-gap absorption threshold caused by shock compression.

shocked GaN do not show any evidence of inelastic deformation for the range of stresses considered here.[23] Hence, the most likely explanation for the abrupt change in the band-gap absorption profile is the activation of Mg acceptors at large stresses.

In conclusion, the optical absorption properties of semi-insulating GaN:Mg have been studied under uniaxial strain conditions through plate-impact shock-wave experiments. The band-gap profiles of shocked and unshocked material are consistent with the theoretical model of Dow and Blossey. Our results point to a decrease of the PZE field for longitudinal stresses larger than 4.6 GPa. This phenomenon may be explained by the dissociation of Mg–H complexes, which results in free holes that screen the PZE field. It was determined that electrical breakdown occurs at a field of approximately 1 MV/cm. In future work, it should be possible to test this value using electrical measurements in shocked GaN:Mg.

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