

Effect of Doping on the Reliability of GaAs Multiple Quantum Well Avalanche Photodiodes

Ilgu Yun, Student Member, IEEE, Hicham M. Menkara, Yang Wang, Ismail H. Oguzman, Student Member, IEEE, Jan Kolnik, Kevin F. Brennan, Gary S. May, Member, IEEE, Christopher J. Summers, and Brent K. Wagner

Abstract—The effect of various doping methods on the reliability of gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) multiple quantum well (MQW) avalanche photodiode (APD) structures fabricated by molecular beam epitaxy is investigated. Reliability is examined by accelerated life tests by monitoring dark current and breakdown voltage. Median device lifetime and the activation energy of the degradation mechanism are computed for undoped, doped-barrier, and doped-well APD structures. Lifetimes for each device structure are examined via a statistically designed experiment. Analysis of variance (ANOVA) shows that dark current is affected primarily by device diameter, temperature and stressing time, and breakdown voltage depends on the diameter, stressing time, and APD type. It is concluded that the undoped APD has the highest reliability, followed by the doped-well and doped-barrier devices, respectively. To determine the source of the degradation mechanism for each device structure, failure analysis using the electron-beam induced current method is performed. This analysis reveals some degree of device degradation caused by ionic impurities in the passivation layer, and energy-dispersive spectrometry subsequently verifies the presence of ionic sodium as the primary contaminant. However, since all device structures are similarly passivated, sodium contamination alone does not account for the observed variation between the differently doped APD’s. This effect is explained by dopant migration during stressing, which is verified by free carrier concentration measurements using the capacitance–voltage (C–V) technique.

I. INTRODUCTION

Gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) multiple quantum well (MQW) avalanche photodiodes (APD’s) are of interest as an ultra-low-noise image capture mechanism for high-definition systems. In this application, the image capture stage must have sufficient optical gain to enable very sensitive light detection, but at the same time, the gain derived during detection must not contribute additional noise. Various APD structures, including doped-barrier, doped-well, and undoped devices have been fabricated, and these structures are all being considered as candidates for the high-definition system imaging application. The effect of the different doping techniques on device performance is critical. An investigation of the relative advantages and disadvantages of each device structure as pertaining to long-term, low-noise performance is therefore warranted.

APD performance is enhanced by minimizing the excess noise generated by carrier multiplication. This excess noise is reduced when the ratio of the ionization rate of electrons to that of holes (or vice-versa) is large. Chin et al. first proposed a means of artificially enhancing the ratio of electron-to-hole ionization coefficients through use of a MQW structure in the GaAs/AlGaAs material system [1]. Later, Brennan analyzed the use of the doped quantum well APD as a photomultiplier [2], and Aristin et al. evaluated various MQW APD structures, including the undoped, doped-barrier, and doped-well devices [3]. These new structures enable very low noise and high-speed APD’s. However, the noise performance of MQW APD’s is limited by dark currents due to both thermionic emission and field-assisted tunneling of carriers out of quantum wells. Therefore, increased dark current can severely limit the long-term reliability of these devices.

Reliability assessment of avalanche photodiodes has been performed by several authors. Sudo et al. conducted accelerated life tests on germanium APD’s to measure their failure rates under practical use conditions [4]. This author also used bias temperature tests and the light-beam induced current method to evaluate lifetime and analyze the failure modes of InP/InGaAs APD’s [5], [6]. Kuhara likewise investigated the long-term reliability of InGaAs/InP photodiodes passivated with polyimide films [7], and Bauer and Trommer performed a similar investigation on devices passivated with silicon nitride [8]. Finally, Skrimshire et al. performed accelerated life tests on both mesa and planar InGaAs photodiodes for comparison purposes [9].

In this paper, accelerated life testing of undoped, doped-barrier, and doped-well APD device structures has been conducted with the objective of estimating long-term device reliability. Since an increase in dark current results in a reduction of the APD signal-to-noise ratio (SNR) and breakdown voltage determines the operational voltage range of the device, these two parameters represent the most sensitive indicators of the characteristic degradation in these devices. Thus, dark current and breakdown voltage were the parameters monitored in this study. Degradation in these parameters was investigated via high temperature storage tests and accelerated life tests, and the results of these tests were used to estimate device lifetime by assuming an Arrhenius-type temperature dependence [10]. Using the median device lifetime and its standard deviation as
parameters, a failure probability model of these devices was derived using a log-normal failure distribution [11].

Lifetimes for each device structure were examined via a statistically designed experiment. A comparison of the reliability of the various APD structures was then performed using the analysis of variance (ANOVA) technique [12]. Results of the ANOVA study revealed which input factors were found to have a significant effect on each response. Dark current was mainly dependent on device diameter, temperature and stress time. Breakdown voltage was primarily impacted by diameter, temperature, and APD type. Based on the results of this investigation, it was concluded that the undoped APD structure yielded devices that exhibited the highest reliability, followed by the doped-well and doped-barrier devices, respectively.

Following device stressing, an analysis was conducted to determine the failure mechanism. Potential failure mechanisms were evaluated using scanning electron microscopy (SEM) and the electron-beam induced current (EBIC) method [13]. Based on SEM and EBIC analysis, the presence of ionic impurities contaminating the passivation layer at the junction perimeter was proposed as a potential failure mechanism. Energy-dispersive spectrometry (EDS) [14] was subsequently used to identify ionic sodium as the source of contamination. However, all three device structures are passivated using the same procedure. Therefore, sodium contamination alone does not account for the observed variation between the differently doped APD device types. On the contrary, this result is explained by dopant migration during stressing, which is verified by the measurement of free carrier concentration before and after stressing using the capacitance–voltage (C–V) technique [15].

II. DEVICE STRUCTURE AND FABRICATION

The device structure of the photodiodes investigated is shown in Fig. 1. The devices were grown by molecular beam epitaxy (MBE) in a Varian Gen-II system at the Georgia Tech Research Institute. The basic structure is that of a p-i-n diode where the intrinsic region is composed of the MQW superlattice structure. All APD’s were composed of a 1-μm Be-doped p+ top layer and a 1.5-μm Si-doped n+ backside layer. The p and n contact layers are doped at a level of 10^{28} cm^{-3} [3]. For the doped-barrier MQW APD’s, the 1–3-μm thick GaAs/AlGaAs superlattice region consists of 25 periods of 200-Å GaAs quantum wells separated by 800-Å AlGaAs barrier layers. One complete period consists of a 300-Å high-field AlGaAs region doped at 10^{28} cm^{-3}, the 200-Å undoped GaAs layer, and a 500-Å undoped AlGaAs layer. In the doped-well devices, high electric fields are achieved in the narrow bandgap GaAs wells of the avalanche region by the introduction of 50-Å thick p+ and n+ layers doped at 1.5 × 10^{28} cm^{-3} [16]. The undoped MQW APD design is similar, but with the MQW region replaced by a 2.5-μm intrinsic AlGaAs/GaAs layer.

The devices were fabricated on 2 × 10^{-4} cm² mesa structures with an active diameter in the range of 75–130 μm using standard photolithographic techniques. Since both the p and n layers can be illuminated by removing the substrate, the device configuration allows for electron or hole injection [17]. A silicon nitride passivation coating suppresses surface leakage current and provides the device with very low dark currents. The fabrication process for these structures is summarized in Fig. 2. The choice of the various fabrication sequences indicated in this figure has a significant effect on device reliability.

III. DEVICE OPERATION

Although electron-hole pairs created in the depletion region are quickly separated by the electric field at the junction in homostructure PIN photodiodes, heterostructure APD’s transform an optical input signal into an electric output signal using an avalanche gain mechanism. In APD’s, the avalanche gain is achieved when the incident or photogenerated free carriers obtain sufficient energy from the electric field to
generate secondary free carriers by impact ionization of the valence electrons into the conduction band, leaving free holes in the valence band. Secondary carriers can then be accelerated by the electric field and generate more carriers by impact ionization of other valence electrons. The generation of electron-hole pairs and avalanche gain depend on the impact ionization rates and the electric field, and the electric field required to observe impact ionization depends on the band gap of the material. As a result of impact ionization, a large number of electron-hole pairs are generated, and a considerably large output signal can be obtained even for relatively small input signals [18].

Reduction of excess noise is crucial if an APD is to detect the low power levels of input signals that result from long wavelength applications. Avalanche multiplication, however, inherently creates extra noise, which adds to the shot noise of the incident carriers. This excess noise results from fluctuation of the avalanche gain. To limit the excess noise caused by avalanche multiplication, holes and electrons must ionize at vastly different rates. Using the multiple quantum well structure, one can artificially tailor the ratio of the ionization coefficients and therefore, reduce excess noise [19]. Examples of the gain and excess noise factors for the MQW APD’s investigated in this study are shown in Figs. 3 and 4.

APD gain and SNR are limited by the dark current in the device, and high dark currents are only exacerbated by the avalanche multiplication process [20], [21]. The resulting increases in dark current due to carrier multiplication lead to reduced SNR. Dark current is therefore perhaps the most important performance parameter used to evaluate APD device reliability. The dark current density in general has the following form [22]:

$$J = \frac{q n_i^2 L_p}{n_o \tau_p} + \frac{q n_i W}{2 \tau_o} + J_T + q \phi_B$$  (1)

where $q$ is the electron charge, $n_i$ and $n_o$ are the intrinsic carrier and majority carrier concentrations, $L_p$ and $\tau_p$ are the minority carrier diffusion length and lifetime, $W$ is the depletion region width, $\tau_o$ is the lifetime of the average of the excess minority carrier electron and hole lifetimes (i.e., $\tau_o = (\tau_{p0} + \tau_{n0})/2$), $\eta$ is the quantum efficiency, $\phi_B$ is the background photon flux, and $J_T$ is the tunneling current. The first, second, third, and fourth terms represent the diffusion, generation–recombination (g–r) tunneling, and background radiation current densities, respectively.

From (1), the diffusion current density is proportional to $(L_p/\tau_p)$, and the g–r current density is proportional to the depletion region width $W$. Since $W$ is a function of the reverse-bias voltage, the g–r current density is also dependent on that voltage. This is especially significant for APD’s operating at the high fields. This factor limits the utility of small band-gap semiconductors for APD’s because they must be operated at high reverse bias voltage. For effective detector performance, low breakdown voltage is a necessity and the three current densities in (1) must be minimized.

**IV. ACCELERATED LIFE TESTING**

**A. Life Test Conditions**

Accelerated life tests for the three different APD structures were performed on several different devices of each type with a constant reverse current of 10 $\mu$A for 200 h at three different...
TABLE I
ACCELERATED LIFE TEST CONDITIONS

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Current [μA]</th>
<th>Number of Samples</th>
<th>Stress Time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>4</td>
<td>260</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>6</td>
<td>260</td>
</tr>
<tr>
<td>200</td>
<td>10</td>
<td>6</td>
<td>209</td>
</tr>
</tbody>
</table>

...ambient temperature levels: 100, 150, and 200 °C. These conditions are summarized in Table I.

The accelerated life tests measured the failure rate under stressful operating conditions. To maintain a constant 10 μA current, the reverse bias voltages for the doped-barrier, doped-well and undoped APD were approximately 8, 10, and 80 V, respectively. The activation energy for the failure mechanism and the average device lifetime were subsequently computed. It was assumed that the temperature dependence of the device failure rate \( R \) obeys the following Arrhenius law [10]

\[
R = R_0 \exp( -E_a / kT )
\]

where \( R_0 \) is a temperature-independent pre-exponential failure acceleration factor, \( E_a \) is the activation energy, \( T \) is the absolute temperature, and \( k \) is Boltzmann’s constant. During these tests, dark current and breakdown voltage were measured at room temperature (300 °K) after high-temperature stressing. The breakdown voltage was obtained from the device \( I-V \) curve using the tangential line method. Typical breakdown voltages were 7.5–9 V for the doped-barrier APD, 10–12 V for the doped-well APD, and 70–85 V for the undoped APD. The devices were classified as failing when the dark currents at room temperature and 90% of the breakdown voltage exceeded 1 μA.

B. Life Test Results

Several observations were made as a result of the high temperature storage tests and accelerated life tests for the GaAs/AlGaAs APD’s. First, unbiased baking of the APD samples resulted in significantly less degradation, which is demonstrated by a comparison of Fig. 5(a) and (b). Dark current increases due to thermal overstress under bias for the doped-barrier devices were generally found to be exponentially dependent on the time of exposure to the reverse-bias field. This fact is shown in Fig. 6(a), in which the dark current at a given reverse-bias voltage increases significantly as a function of stress time. On the other hand, breakdown voltage was shown to be nearly linearly dependent on stressing time, as shown in Figs. 6(b). The doped-well and undoped devices exhibited similar behavior.

Fig. 7 depicts a sample plot of the percent of cumulative failures for the doped-barrier devices versus the lognormal projection of the device time-to-failure after accelerated life testing. Although the sample size is small, in each case the data appears linear, which indicates that the failure mode is the wearout type. Failures obey the lognormal distribution relatively well. Median lifetimes for the doped-barrier devices at 100, 150, and 200 °C were estimated to be 1400, 250, and 78 h, respectively, with a standard deviation of 1.94. Finally, in the undoped case, the median lifetimes at 100, 150, and 200 °C are estimated to be 8590, 495, and 84 h, respectively, with a standard deviation of 2.13.

A sample Arrhenius plot of median lifetimes as a function of reciprocal aging temperature is shown in Fig. 8. From plots such as this, the thermal activation energy of the device aging process is computed to be 0.44, 0.60, and 0.71 eV for the doped-barrier, doped-well, and undoped devices, respectively. Using these activation energy levels, the median APD lifetime for the doped-barrier device under practical use conditions can be estimated to be \( 3.3 \times 10^4 \) h (approximately 4.3 yr) at room temperature, with a standard deviation of 116 h. Lifetime estimates for the doped-well and undoped cases were \( 3.0 \times 10^3 \) h (approximately 39 yr) with a standard deviation of 343 h and \( 2.17 \times 10^4 \) h (approximately 197 yr) at room temperature, with a standard deviation of 1031 h. It is interesting to note that the doped-well APD, which is a complimentary structure of the...
doped-barrier APD, has a significantly longer median lifetime. A summary of life test results is shown in Table II.

Due to the lognormal degradation behavior of the APD’s, the failure probability of each device as a function of time, $P(t)$, may be computed from the lognormal failure model by using the average device lifetime ($\mu$) and its standard deviation ($\sigma$) as [11]

$$P(t) = \frac{1}{\sigma \sqrt{2\pi}} \int_{0}^{t} \frac{1}{t} \exp \left[ -\frac{(\ln t - \mu)^2}{2\sigma^2} \right] dt.$$  \hspace{1cm} (3)

Along with the lognormal plot, this expression provides a quantitative method of evaluating the likelihood of failure for a given device as a function of its age.

V. PERFORMANCE COMPARISON OF APD STRUCTURES

Statistical experimental design [12] was used to quantify the impact of each factor on APD reliability and to determine whether the differences between device structures were statistically significant. Due to the mixture of qualitative and quantitative input factors, a $D$-optimal experimental design with 24 runs was selected to identify the effect of input parameters on the measured responses [23]. The factors investigated in this experiment were device type, diameter of the active area, aging temperature, and stress time. A summary of these input factors is shown in Table III. Dark current, breakdown voltage, and device lifetime were the measured responses.

A comparison of the various APD structures in terms of reliability was performed using the ANOVA technique. Experimental data were analyzed using the RS/Discover commercial software package [24]. Using this approach, it was verified that the different processes used to fabricate the three APD structures did indeed significantly impact the reliability of the devices. Using the ANOVA technique, the statistical significance of each input reflects the degree to which the parameter contributes to the variation of the measured responses. If the value of the statistical significance is less than 5%, then the input contribution to the variation of the measured response is
considered significant with 95% confidence. Table IV shows the significance of each factor on the two responses.

Results indicate that dark-current variation is affected primarily by diameter, temperature, stressing time, and to a lesser degree, by the APD type. Breakdown-voltage variation depends on the diameter, stressing time, and APD type. Interestingly, the stress temperature did not have a significant effect on the change in breakdown voltage. Finally, the device lifetime is impacted most significantly by stress temperature and APD type.

![Fig. 9. SEM image of GaAs MQW APD before accelerated life testing.](image)

From these results, it may be concluded that the doping process used in the fabrication of the APD structure has a profound impact on device reliability. Since the undoped devices exhibit the highest degree of reliability, it can be assumed that doping, while enhancing device performance in other ways [2], [3] makes the device less reliable. Specific causes for the observed differences in device degradation are explored in Section VI.

VI. FAILURE ANALYSIS

A. SEM and EBIC Analysis

Failure analysis on the thermally stressed doped-barrier, doped-well and undoped devices was carried out using scanning electron microscopy (SEM) and the electron-beam induced current (EBIC) method [13]. Prior to this analysis, the presence of contaminants in passivating nitrides at the junction was hypothesized as a possible cause for dark current increases during stressing.

Fig. 9 shows an SEM image of a doped-barrier device prior to accelerated life testing. This image shows no discernible defects. However, defects causing device failure were detected in each type of device after life testing (see Fig. 10). Similar results were observed in the doped-well and undoped devices.

Using EBIC analysis, local defects at the junction region change the electron-beam current indicating the reason for the device failure. Defects near the area of the junction were detected in the EBIC images, and nearly all the SEM images exhibit a similar pattern of defects in the exposed junction area as well. The only exception was the SEM image of an undoped device after life testing, which showed only a small defect in the junction.

B. EDS Analysis

From SEM and EBIC analysis of the degraded samples, it was determined that the dark current increase could be partially explained by the presence of ionic impurities or contamination in the silicon nitride passivation layer at the...
junction perimeter. Such contamination generates a leakage path shorting the junction under an electric field. This hypothesis is supported by the fact that unbiased baking of the APD samples resulted in significantly less degradation (see Fig. 5). It has been suggested that these type of defects occur at metal-rich precipitates, some of which occur at crystal dislocations [5]–[7]. The cause of the gradual reduction in breakdown voltage, on the other hand, is not known explicitly, but presumably involves the field-assisted and/or temperature-assisted drift of some impurity species or defects to localized sites in the pn junction.

A common contaminant for silicon nitride passivating films is ionic sodium. Energy-dispersive spectrometry (EDS) was used to determine whether sodium was the source of contamination in these devices [25]. Using EDS analysis, the composition of a sample and the quantity of each element of a composite material can be obtained. In this case, EDS confirmed the presence of ionic sodium and verified that sodium is the primary contaminant (see Table V). It is believed that this sodium originated from the APD processing environment or the personnel involved in fabrication. In addition, ionic potassium was detected in the doped-barrier device. (The significant amount of phosphorus detected in the undoped device was probably due to the etching of the mesa structure).

C. Dopant Migration Effects

Although ionic contamination is a plausible explanation for device degradation, this effect alone does not account for the statistically significant variations in lifetime among the differently doped APD structures. Since the same passivation process was applied to each structure, one would expect that each would have roughly the same lifetime if contamination were the sole cause of degradation. However, it was observed that the undoped devices were clearly more reliable, followed by the doped-well and doped-barrier devices, respectively. Therefore, it was theorized that dopant migration might also play a significant role in the device degradation mechanism. This theory was investigated by analyzing dopant migration using $C$–$V$ measurements to extract the free carrier concentration in the APD multiple quantum well region before and after life testing. $C$–$V$ measurements were performed at 1 MHz using an HP4277A LCZ meter.

For the doped-barrier APD, the free carrier profile in the depletion region is shown in Fig. 11. Before life testing, the depletion region width under reverse bias near the breakdown voltage is approximately 0.195 $\mu$m. After life testing, the free carrier concentration significantly increases in the barrier region, and the depletion width decreases to 0.14 $\mu$m under reverse bias. Similarly, for the doped-well APD, the free carrier profile before and after life testing appears in Fig. 12. Before life testing, the depletion region width under reverse bias is about 0.185 $\mu$m. After life testing, the free carrier concentration again increases, and the depletion width shrinks to 0.17 $\mu$m.

The free carrier profiles in Figs. 11 and 12 are similar to those reported by Aristin et al. for a doped-barrier MQW APD structure [26]. That paper stated that as the doping concentrations in the barrier increase, dark current increases and breakdown voltage decreases. In the present investigation, the free carrier concentrations increased in doped-barrier layers after life testing as well, resulting in comparable increases in dark current.
From the results of the $C-V$ measurements, it is hypothesized that during the life test, the thermally and electrically excited dopants obtain sufficient energy to migrate into the passivation layer, which causes an increase in free carrier concentration in this region. After entering the passivation layer, these dopants behave similarly to positive surface charges. Because of the accumulation of positive charge, the depletion width is reduced and the electric field in the region where the p-n junction intersects the passivation layer is more intense. Dark current is increased by both the positive charge accumulation as well as the intensified electric field in the narrow depletion region associated with the passivation layer. These increases accelerate the degradation of the device, eventually resulting in failure. The effect is more pronounced in the doped-barrier devices since the observed shrinkage in the depletion region width is greater in these devices than in the doped-well APD.

**VII. CONCLUSION**

This paper has presented accelerated life tests of doped-barrier, doped-well, and undoped AlGaAs/GaAs multiple quantum well avalanche photodiodes from the viewpoint of evaluating long-term reliability. From the life test results, the activation energy of the degradation mechanism and median lifetime of these devices were determined. In addition, the failure probability of the devices was computed from the log-normal failure model by using the average lifetime and the standard deviation of that lifetime as parameters.

Using the ANOVA technique, a comparison of the reliability of the various APD structures was undertaken. Based on this investigation, it was concluded that the doping process used in the multiple quantum well APD fabrication has a significant effect on device reliability. It was found that the undoped APD structure yielded devices that exhibited the highest reliability, followed by the doped-well and doped-barrier devices, respectively.

Subsequent failure analysis using the SEM and EBIC methods clarified that the dark current increase was in part brought about by the presence of ionic contaminants in the passivation layer at the junction perimeter that generate a leakage path which shorts the junction under the effect of electric field. EDS analysis identified the primary contaminant as ionic sodium. In addition, dopant migration under stress was theorized as a means to explain the observed reliability differences between the device structures. This dopant migration was investigated using $C-V$ measurements, which verified that the redistribution of free carriers after stress is indeed a plausible explanation for reliability differences between differently doped devices.

**ACKNOWLEDGMENT**

The authors would like to thank A. Doolittle for his aid in performing EBIC measurements and for many helpful discussions.

**REFERENCES**

YUN et al: EFFECT OF DOPING ON RELIABILITY OF GaAs MQW APD’S


[27] Ilgu Yun (S’96) received the B.S. degree in electrical engineering from Yonsei University, Seoul, Korea, in 1990, and the M.S. degree in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, in 1995. He is currently a Ph.D. candidate in the School of Electrical and Computer Engineering, the Georgia Institute of Technology. His research interests include high-field, high-energy transport physics in compound semiconductors and modeling and simulation of novel semiconductor devices.

[28] Hicham M. Menkara was born in Lebanon on August 31, 1968. He received the B.S. degree (magna cum laude) in engineering physics from the University of Toledo, Toledo, OH, in 1989, and the M.S. degree in physics and electrical engineering, and the Ph.D. degree in physics from the Georgia Institute of Technology, Atlanta, in 1990, 1993, and 1996, respectively. He also received the M.S. degree in management from Georgia Tech in September 1996. Currently, he is a Professional Advisor for the Georgia Tech Research Institute. His current research interests include experimental analysis and TCAD modeling of optoelectronic devices such as avalanche photodiodes and phosphor-based structures.

[29] Kevin F. Brennan was born in Elizabeth, NJ, on October 18, 1956. He received the B.S. degree in physics from the Massachusetts Institute of Technology, Cambridge, in 1978, and the M.S. degree in physics and the Ph.D. degree in electrical engineering from the University of Illinois, Urbana-Champaign, in 1984. Currently, he is an Institute Fellow and Professor in the School of Electrical and Computer Engineering, Georgia Tech Research Institute, Atlanta. His current research interests include the physics and modeling of semiconductor devices. Of particular interest are the physics and modeling of avalanche photodiodes, confined state ionization devices, high field and degeneracy effects in semiconductors, photoconductors, and high-speed transistors.

Dr. Brennan is a recipient of a Presidential Young Investigator Award through the National Science Foundation.

[30] Ismail H. Oguzman (S’92) was born in Istanbul, Turkey, on May 26, 1967. He received the B.S. degree in electrical engineering from Istanbul Technical University, Istanbul, Turkey, in 1989, and the M.S. degrees in physics and electrical engineering, from the Georgia Institute of Technology, Atlanta, in 1990 and 1993, respectively. He is currently pursuing the Ph.D. degree in electrical engineering at Georgia Tech. His dissertation work involves high-field, high-energy transport physics in compound semiconductors and modeling and simulation of novel semiconductor devices.

[31] Jan Kolnik received the Dipl. Ing. degree from the Slovak Technical University, Bratislava, Slovakia, in 1981. Currently, he is pursuing the Ph.D. degree at the Georgia Institute of Technology, Atlanta.

From 1982 to 1992, he was with the Institute of Physical Electronics of Slovak Academy of Sciences. His research interests include modeling on impact ionization and simulation of high-speed transport in compound semiconductors and modern semiconductor devices.

[32] Dr. Wang is a member of Sigma Xi and the Scientific Research Society.
Gary S. May (S’85–M’90) received the B.S. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, in 1985 and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of California, Berkeley, in 1987 and 1991, respectively. He was a National Science Foundation and an AT&T Bell Laboratories graduate Fellow, and has worked as a member of the technical staff at AT&T Bell Laboratories, Murray Hill, NJ. Currently, he is an Associate Professor in the School of Electrical and Computer Engineering and Microelectronics Research Center, Georgia Institute of Technology. His research is in the field of computer-aided manufacturing of integrated circuits, and his interests include semiconductor process and equipment modeling, process simulation and control, automated process and equipment diagnosis, and yield modeling. Dr. May is a National Science Foundation “National Young Investigator,” and is an Associate Editor of the IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING. He is Chairperson of the National Advisory Board of the National Society of Black Engineers (NSBE).

Christopher J. Summers received the B.S. and Ph.D. degrees in physics from Reading University, Reading, U.K., in 1962 and 1966, respectively. He joined the Georgia Tech Research Institute, Georgia Institute of Technology, Atlanta, in 1981 and is currently a GTRI Fellow and Chief of the Quantum Microstructure Branch. His research interests include optoelectronic properties of heterostructures, molecular beam epitaxy of II–VI and III–V semiconductors, and the growth and characterization of phosphor materials.

Brent K. Wagner received the B.S. degree in engineering science from the Pennsylvania State University, University Park, in 1984, and the M.S. degree in physics and the Ph.D. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, in 1987 and 1991, respectively. Currently, he is a Research Scientist at the Georgia Tech Research Institute. His research interests include the thin-film growth and characterization of II–VI and III–V semiconductors and phosphor materials and the application of heterostructures to optoelectronic devices.