Minority Electron Transport Anisotropy in P-Type $Al_xGa_{1-x}N$/GaN Superlattices

Leonid Chernyak, *Senior Member, IEEE*, Andrei Osinsky, *Member, IEEE*, Vladimir N. Fuflyigin, John W. Graff, and
E. Fred Schubert, *Fellow, IEEE*

***Abstract*—The minority electron diffusion length, L, in Mg-doped molecular beam epitaxy (MBE) grown p-type $Al_xGa_{1-x}N$/GaN superlattices with aluminum content $x = 0.1$ and 0.2 was measured perpendicular and parallel to the superlattice planes by the electron beam induced current (EBIC) technique. A large anisotropy in the transport properties was observed with the effect varying from 1 : 3 to 1 : 6. We attribute an experimentally observed diffusion length anisotropy to minority electron scattering during transport across the potential barriers of the superlattice. Reference p-GaN samples were also investigated, and the diffusion length was observed to be isotropic in both metal-organic chemical vapor deposition (MOCVD) ($L = 0.5$ μm) and MBE ($L = 0.27$ μm) grown samples.**

***Index Terms*—Electron microscopy, semiconductor materials, superlattices.**

I. INTRODUCTION

THE USE OF wide bandgap (WBG) semiconductors such as GaN and SiC has proven to result in superior electron device performance for microwave applications. The unipolar electron devices based on WBG heterostructures, such as AlGaN/GaN heterojunction field effect transistors (HFETs), can deliver microwave powers over 10 W/mm with high power added efficiency (PAE), f_t and $f_{\max}$ [1]. These devices have already outperformed Si-based counterparts, which are represented by lateral drain metal oxide semiconductor (LDMOS) technology. On the other hand, heterojunction bipolar transistors (HBTs) are known to possess fundamentally superior figures of merits as compared to unipolar HFETs.

The key problem with demonstrating high performance HBTs in (Al)GaN system is poor conductivity of the p-(Al)GaN layers, which are used for a thin base. This results in a high spreading and Ohmic contact resistance, translating into low gains and a high microwave parasitic current.

To enhance hole conductivity in the base, the p-AlGaN/GaN superlattice structures, fabricated involving modulation doping mechanism [2], [3], can be used. Even though high lateral conductivity was demonstrated in such structures, the vertical conductivity across the superlattice layers, which is an important transport property of the HBTs, has not yet been studied.

Since AlGaN/GaN superlattice is a good candidate for low access resistance base layers in n-p-n AlGaN/GaN HBTs [4]–[6], the understanding of electron transport in this superlattice system is of significant importance. Minority carrier diffusion length L is the crucial material parameter for the base of the HBT, affecting the device design and overall performance. Besides other factors, the importance of the latter parameter is determined by a vertical architecture of HBTs [4], [6]. Due to this architecture, carriers may experience multiple scattering events when transferred from the emitter, through a series of AlGaN/GaN superlattice potential barriers, to the collector. Here, we report for the first time on the anisotropy of minority carrier (electron) diffusion length in $Al_xGa_{1-x}N$/GaN superlattices.

II. EXPERIMENTAL

Molecular beam epitaxy (MBE) was employed to grow the $Al_xGa_{1-x}N$/GaN ($x = 0.1$ and 0.2) superlattice structures [cf. Fig. 1(a)]. The 0.4 μm thick structures were grown above a 1.0 μm layer of highly resistive (i) GaN on c- sapphire substrates. The growth temperature was kept at ~700 °C and p-type doping was performed by co-evaporation of Mg from a solid source Knudsen cell. The $Al_{0.1}Ga_{0.9}N$/GaN superlattice (referred to hereafter as SLA) contained 20 periods with a well and barrier thickness of 10 nm each. Two types of superlattices were grown with 20% aluminum. These structures comprised 20 periods, with 5 nm well and 15 nm barrier thickness (SLB) in one, and vice versa in the other (SLC). Layer thickness was confirmed by X-ray diffraction following analysis of the full-width at half-maximum and the intensities of the (0002) reflection. The majority carrier concentration and mobility in the layers were determined by room temperature Hall effect measurements. The measured parameters were $p = 2 \times 10^{18}$ cm^{-3} and $\mu = 1$ cm^2/Vs (for $x = 0.1$), and $p = (2.5-4) \times 10^{17}$ cm^{-3} and $\mu = $ 1–2 cm^2/Vs (for $x = 0.2$). 1–2 μm thick reference p-GaN layers (see Table I), grown by MBE and MOCVD on sapphire substrates according to the scheme shown in Fig. 1(a), were also examined. These layers demonstrated a hole concentration of 2×10^{17} cm^{-3} with a mobility of ~3.5 and 7 cm^2/Vs for the MBE and MOCVD samples, respectively.

The electron beam induced current (EBIC) technique was used to determine the minority carrier diffusion length. EBIC

Manuscript received April 3, 2000; revised October 31, 2000. This work was supported in part by NSF SBIR Grant DMI-9760579 and BMDO STTR under Contract N0014-99-M-0277 managed by ONR and monitored by J. Zolper and ONR Grant N00014-98-1-0194 monitored by C. Wood. The review of this paper was arranged by Editor J. C. Zolper.

L. Chernyak is with the Department of Physics, University of Central Florida, Orlando, FL 32816-2385 USA (e-mail: chernyak@physics.ucf.edu).

A. Osinsky and V. N. Fuflyigin are with Corning Applied Technologies, Woburn, MA 01801 USA.

J. W. Graff and E. F. Schubert are with the Department of Electrical Engineering, Boston University, Boston, MA 02215 USA.

Publisher Item Identifier S 0018-9383(01)01449-6.

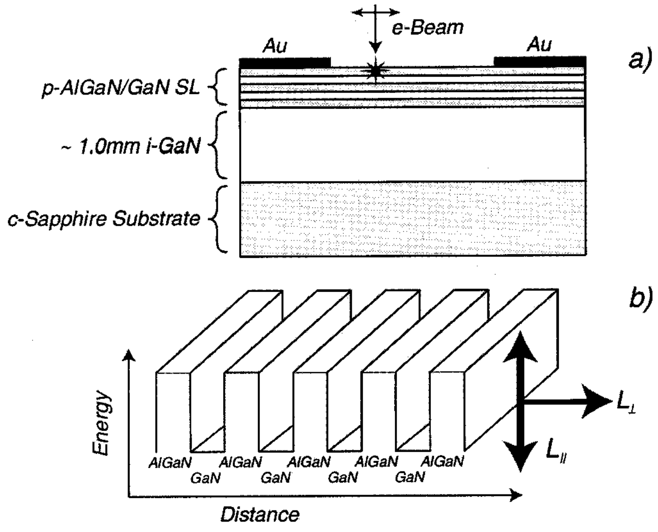

Fig. 1. (a) Scheme of EBIC measurements carried out on AlGaN/GaN superlattice structures and GaN samples. EBIC line-scan is parallel to these layers during $L_{||}$ measurements and perpendicular to them during $L_\perp$ measurements. (b) Energy diagram, corresponding to AlGaN/GaN superlattice potential barriers. Directions, corresponding to $L_{||}$ and $L_\perp$ measurements, are denoted by arrows.

TABLE I
SUMMARY OF EXPERIMENTAL RESULTS

Sample	Majority carrier Concentration, cm^{-3}	Mobility, cm^2/Vsec	Diffusion length, $L_{//}$, μm	Diffusion length $L_\perp$,μm	Ratio $L_{//}/L_\perp$
SLA $Al_{0.1}Ga_{0.9}N/GaN$ (10/10 nm = well/barrier)	2x10^{18}	1.0	0.26	0.08	3.25
SLB $Al_{0.2}Ga_{0.8}N/GaN$ (5/15 nm = well/barrier)	4x10^{17}	2.0	0.47	0.08	5.85
SLC $Al_{0.2}Ga_{0.8}N/GaN$ (15/5 nm = well/barrier)	2.5x10^{17}	1.0	0.3	0.1	3.0
MOCVD-GaN (2 μm-thick)	2x10^{17}	7.0	0.5	0.51	~ 1
MBE-GaN (1.0 μm-thick)	2x10^{17}	3.5	0.27	0.27	1

was performed *in-situ* in a JEOL 6400F Scanning Electron Microscope (SEM) under 10 kV acceleration voltage, corresponding to an electron range, R, of 0.36 μm [7] and measured injected current of 0.13 nA. A planar metal-semiconductor (Schottky) configuration, shown in Fig. 1(a), was used for the measurements. Schottky diodes were formed by evaporation of 1500 Å of gold followed by a lift off technique, resulting in a pattern of 2×2 mm contact pads. A much larger Au pad served as a quasiohmic contact. The current—voltage (*I–V*) characteristics of the samples were measured to behave like Schottky diodes. In the EBIC measurements, the electron beam was scanned away from the edge of a Schottky barrier [see Fig. 1(a)] [8]. Separate measurements were made while scanning both parallel and perpendicular (on the cleaved samples) to the superlattice plane. A direct method for the extraction of diffusion length, L, from the EBIC line-scan was adopted from [7]. A number of EBIC researchers have used the EBIC line-scan measurements for minority carrier diffusion length extraction in GaN and AlGaN epitaxial films of *finite thickness* [9]–[14].

EBIC current, I, decays with the beam-to-junction distance, d, according to the relationship

$$I = Ad^{\alpha} \exp\left(-\frac{d}{L}\right) \tag{1}$$

where A is a constant and α is a coefficient depending on the surface recombination velocity, v_s. It has been reported that α varies between -0.5 (for $v_s = 0$) and -1.5 (for $v_s = \infty$) [15]. In this work, α was chosen to be -0.5, similar to that of other groups [9]–[13]. We note that even if an arbitrary value of α (in the -0.5 to -1.5 range) is used, the results change by less than 20%. This is since the dominant term in equation (1) is an exponent, which does not contain α. The diffusion length of minority carriers can be obtained from (1) as $-1/slope$, if $\ln(Ixd^{1/2})$ is plotted versus d, for $d > 2L$ [15]. We also note that since a minority carrier diffusion length of $Al_xGa_{1-x}N$/GaN superlattice samples in the direction perpendicular to the growth plane is $\sim$4 times smaller than epilayer thickness, these samples can be considered as bulk material [16].

Since both contacts, used in the EBIC measurements, are fabricated on the top surface of the structures under investigation [cf. Fig. 1(a)], an internal electric field, existing at the interface between the p-type epilayer and underlying highly resistive i-GaN, does not play a role in carrier collection. This is because the i-part of the structures is floating. Our assumption is confirmed by independent references [17], [18] in which the effect of the back surface field has been studied. In particular, [17] reported on the EBIC measurements in the planar vertical p^+-n-p structures. It was noted, that for the EBIC measurements in the n-type base region, where the diffusion length is generally greater than that in the emitter (p^+-region), some of the generated minority carriers can reach the base-collector junction. These carriers are pushed through the base-collector junction toward the collector, due to the built-in electric field, existing in the space-charge region of this junction. But these carriers do not create a current in the EBIC circuit, since the collector is left open (only the emitter-base junction is connected to the EBIC amplifier). Because of these lost carriers, the EBIC will be lessened; but this should not affect the value of L, which depends, according to the equation (1), only on the slope of the EBIC current.

III. RESULTS AND DISCUSSION

We first examined the SLA structure. Fig. 2 shows $\ln(Ixd^{1/2})$ plotted versus distance from the Schottky barrier in both, the parallel and perpendicular directions. A large difference in the slope for each direction indicates anisotropy in the electron diffusion length. The calculated values of electron diffusion length,

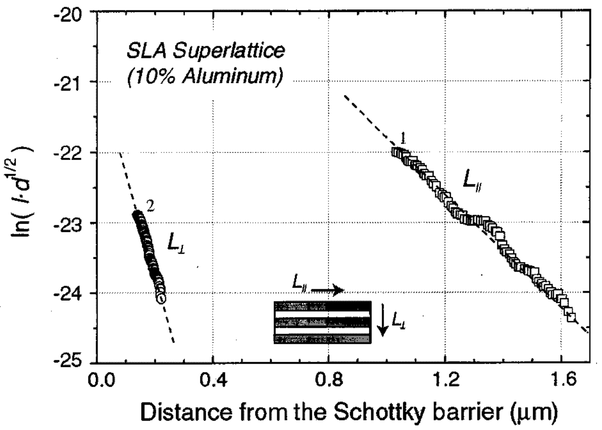

Fig. 2. Plot of $\ln(Ixd^{1/2})$ versus distance, d, from the Schottky barrier for $Al_{0.1}Ga_{0.9}N$/GaN superlattice structure. Straight lines represent a linear fit of the experimental data (open squares and circles). The electron diffusion length is derived from the slopes of lines 1 and 2. Line 1 corresponds to the EBIC line-scan in the direction parallel to the growth plane; line 2 corresponds to the EBIC line-scan in the direction perpendicular to the growth plane.

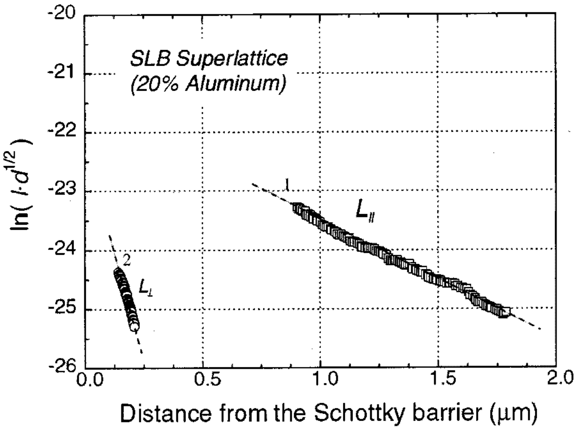

Fig. 3. Plot of $\ln(Ixd^{1/2})$ versus distance, d, from the Schottky barrier for $Al_{0.2}Ga_{0.8}N$/GaN superlattice structure (SLB). $L_{\|}$ and $L_{\perp}$, obtained from the lines 1 and 2, are 0.47 and 0.08 μm, respectively.

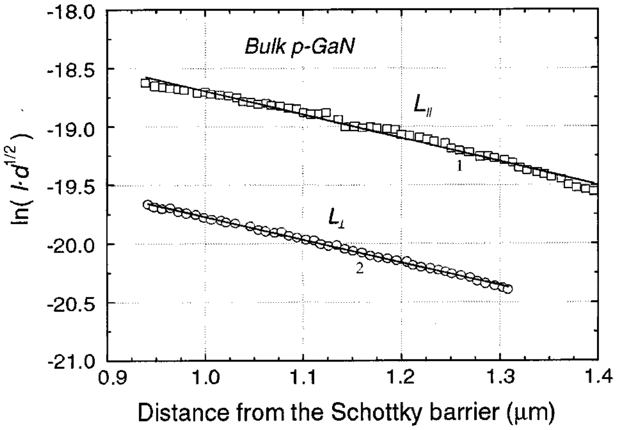

Fig. 4. Plot of $\ln(Ixd^{1/2})$ versus distance, d, from the Schottky barrier for the reference MOCVD-grown p-GaN sample. $L_{\|}$ and $L_{\perp}$, obtained from the inverse slopes of lines 1 and 2, are ~0.5 μm in both cases. Note that the lines 1 and 2 are parallel.

$L_{\|}$ and $L_{\perp}$, were found to be 0.26 and 0.08 μm for the parallel and perpendicular directions, respectively.

Similar anisotropy was observed in the superlattices with 20% aluminum, and the EBIC current versus distance dependence for SLB is shown in Fig. 3. The values of the electron diffusion lengths were determined to be 0.47 μm (SLB) and 0.3 μm (SLC), for the parallel direction, and 0.08 μm (SLB) and 0.1 μm (SLC), for the perpendicular one.

The electron diffusion length was also measured on bulk p-GaN samples. For both MOCVD and MBE samples, no anisotropy in the transport properties was observed. Fig. 4 shows the EBIC current versus distance dependence for the MOCVD sample. This result is not unexpected, due to the high crystal quality of the bulk material. Although the dislocation density varies in bulk GaN as a function of depth, this does not affect $L_{\perp}$. This is because for the EBIC measurements perpendicular to the growth plane, the electron beam line-scan is parallel to the threading dislocations. This prevents carrier scattering on dislocation walls. On the other hand, our recent studies have shown that in quasibulk GaN, minority carrier diffusion length depends on the density of threading dislocations, when the EBIC line-scan is carried out perpendicular to them (i.e., parallel to the plane of growth) at variable depth from the GaN surface. L decreases from 0.63 to 0.25 μm, for the dislocation density varying between 10^8 to 10^9 cm^{-2} [19]. Diffusion length measurements for all the samples in this study are summarized in Table I. We note that there is no EBIC resolution limitation in our case, since the ratio R/L is ≤ 4 [20].

The observed anisotropy in the diffusion length for the superlattice samples is expected, due to the potential barriers limiting electron propagation across the layers [cf. Fig. 1(b)]. Since $L_{\perp}$ (≈100 nm) for the superlattices under investigation is much larger than the barrier and well widths, the comparison of the superlattices with unequal barriers and wells is justified. Minority carriers are likely to experience multiple scattering on the walls of the superlattice, resulting in much lower diffusion length in the perpendicular direction. Similar effect was observed by us in naturally ordered layers of $GaInP_2$ alloys with $CuPt_B$-type ordering [21]. In the direction parallel to the superlattice planes, the diffusion length was measured to be greater for the SLB with higher aluminum content and thinner well. This might be related to larger minority carrier mobility in this structure (assuming the same trend in majority and minority carrier mobility; cf. Table I), which could explain the larger diffusion length.

An additional factor that may affect the diffusion length in the AlGaN/GaN superlattice structures is the presence of strong electric fields, caused by spontaneous and piezoelectric polarization [22]. The electric fields result in spatial separation of electrons and holes within the potential wells of the superlattice, thereby increasing the minority carrier lifetime (as determined from time-resolved photoluminescence measurements) and, hence, diffusion length. Larger field in the thin well 20% aluminum sample could cause a more pronounced spatial separation of carriers and, therefore, larger diffusion length [23].

IV. CONCLUSIONS

EBIC measurements of minority carrier diffusion length have been performed on p-type AlGaN/GaN superlattice structures. A large anisotropy was observed in the transport properties for directions parallel and perpendicular to the superlattice planes. This anisotropy is explained by scattering of minority electrons at the walls of potential barriers of the superlattice. Diffusion length measurements on reference p-GaN layers showed no such anisotropy. The small diffusion length, measured in the superlattice samples perpendicular to the plane of growth, shows that p-AlGaN/GaN structures, used as base layers, are unlikely to improve performance of vertical geometry HBTs, unless a diffusion length is increased. Our recent results show that this can be achieved by electron injection into the p-type base region and subsequent charging of deep Mg-related traps [24].

ACKNOWLEDGMENT

The authors would like to thank E. Waldron for help with the Hall measurements.

REFERENCES

[1] S. J. Pearton *et al.*, "GaN processing, defects and devices," *J. Appl. Phys.*, vol. 86, pp. 1–78, 1999.

[2] E. F. Schubert *et al.*, "Enhancement of deep acceptor activation in semiconductors by superlattice doping," *Appl. Phys. Lett.*, vol. 69, pp. 3737–3739, Dec. 1996.

[3] I. D. Goepfert, E. F. Schubert, A. Osinsky, and P. E. Norris, "Efficient acceptor activation in $\mathrm{Al}^x\mathrm{Ga}^{1-x}\mathrm{N}$/GaN doped superlattices," *Electron. Lett.*, vol. 35, pp. 1109–1111, June 1999.

[4] B. S. Shelton *et al.*, "AlGaN/GaN heterojunction bipolar transistors grown by metal organic chemical vapor deposition," *Electron. Lett.*, vol. 36, pp. 80–81, Jan. 2000.

[5] P. M. Asbeck *et al.*, "Enhancement of base conductivity via the piezoelectric effect in AlGaN/GaN HBTs," *Solid-State Electron.*, vol. 44, pp. 211–219, Feb. 2000.

[6] L. S. McCarthy *et al.*, "AlGaN GaN heterojunction bipolar transistor," *IEEE Electron. Device Lett.*, vol. 20, pp. 277–279, June 1999.

[7] L. Chernyak *et al.*, "Electron beam induced current measurements of minority carrier diffusion length in gallium nitride," *Appl. Phys. Lett.*, vol. 69, pp. 2531–2533, Oct. 1996.

[8] D. E. Ioannou and C. A. Dimitriadis, *IEEE Trans. Electron. Devices*, vol. ED-29, pp. 445–450, Mar. 1982.

[9] Z. Z. Bandić *et al.*, "Minority carrier diffusion length and lifetime in GaN," *Appl. Phys. Lett.*, vol. 72, pp. 3166–3168, June 1998.

[10] Z. Z. Bandić *et al.*, "Electron diffusion length and lifetime in p-type GaN," *Appl. Phys. Lett.*, vol. 73, pp. 3276–3278, Nov. 1998.

[11] Z. Z. Bandić *et al.*, "The values of minority carrier diffusion lengths and lifetimes in GaN and their implications for bipolar devices," *Solid-State Electron.*, vol. 44, pp. 221–228, 2000.

[12] A. Cremades *et al.*, "Effects of phase separation and decomposition on the minority carrier diffusion length in $\mathrm{Al}^x\mathrm{Ga}^{1-x}\mathrm{N}$ films," *J. Appl. Phys.*, vol. 87, pp. 2357–2362, Mar. 2000.

[13] A. Cremades *et al.*, "Minority carrier diffusion length in AlGaN: A combined electron beam induced current and transmission microscopy study," *Solid State Phenom.*, vol. 63–64, pp. 139–146, 2000.

[14] T. Miyajima *et al.*, "Minority carrier diffusion length in GaN and ZnSe," *J. Cryst. Growth*, vol. 189/190, pp. 768–772, 1998.

[15] D. S. H. Chan *et al.*, "A direct method for the extraction of diffusion length and surface recombination velocity from an EBIC line scan: Planar junction configuration," *IEEE Trans. Electron. Devices*, vol. 42, pp. 963–968, May 1995.

[16] C. A. Dimitriadis, "Determination of bulk diffusion length in thin semiconductor layers by SEM-EBIC," *J. Phys. D: Appl. Phys.*, vol. 14, pp. 2269–2274, 1981.

[17] A. Boudjani *et al.*, "Direct measurement of minority carrier diffusion length in planar devices," *Solid-State Electron.*, vol. 38, pp. 471–475, 1995.

[18] O. von Ross *et al.*, "Analysis of the interaction of an electron beam with back surface field solar cells," *J. Appl. Phys.*, vol. 54, pp. 3938–3942, July 1983.

[19] L. Chernyak *et al.*, "Electron beam and optical depth-profiling of quasibulk GaN," *Appl. Phys. Lett.*, vol. 77, pp. 2695–2697, Oct. 2000.

[20] K. L. Luke *et al.*, "Quantification of the effects of generation volume, surface recombination velocity, and diffusion length on the electron-beam-induced current and its derivative: Determination of diffusion lengths in the low micron and submicron ranges," *J. Appl. Phys.*, vol. 57, pp. 1978–1984, Mar. 1985.

[21] L. Chernyak, A. Osinsky, H. Temkin, and A. Mintairov *et al.*, "Transport anisotropy in spontaneously ordered GaInP^2 alloys," *Appl. Phys. Lett.*, vol. 70, pp. 2425–2427, May 1997.

[22] C. Monier *et al.*, "Oscillator strength of excitons in (In, Ga) As/GaAs quantum wells in the presence of a large electric field," *J. Appl. Phys.*, vol. 85, pp. 2713–2718, Mar. 1999.

[23] E. L. Waldron, E. F. Schubert, and J. W. Graff *et al.*, *Evidence of Polarization Effects in Doped* $\mathrm{Al}^x\mathrm{Ga}^{1-x}\mathrm{N}$*/GaN Superlattices*, 2000.

[24] L. Chernyak *et al.*, "Electron beam-induced increase of electron diffusion length in p-type GaN and AlGaN/GaN superlattices," *Appl. Phys. Lett.*, vol. 77, pp. 875–877, Aug. 2000.

Leonid Chernyak (SM'99) studied semiconductor device physics at Lvov Technical University, Lvov, Ukraine. He received the M.Sc. in 1986, and the Ph.D. degree in 1996 from the Weizmann Institute of Science, Israel. His dissertation was on electric field-induced changes of local properties and microcomposition of semiconductors.

He worked for several years in industry. After completing the Ph.D. degree, he was a Postdoctoral Fellow at Colorado State University, Fort Collins, and Texas Tech, concentrating on the optical and electronic properties of GaN and GaP. In 1996, he joined Intel Corporation as Member of Technical Staff. He was with Intel R&D headquarters, Santa Clara, CA, and Chandler, AZ, and with Qiryat Gat, Israel, focusing on the different aspects of flash memory and logic technologies. He joined the Physics Department, University of Central Florida, Orlando, in November 1999. His research is focused on electron injection-induced effects in GaN and AlGaN semiconductors.

Andrei V. Osinsky (M'00) was born in Minsk, Belarus, in 1966. He received the M.S. degree in electrical engineering in 1989 from National Polytechnical University, Kiev, Ukraine, and the Ph.D. degree in electrical engineering from the A.F. Ioffe Phys-Tech Institute, Russia, in 1994.

He was a Visiting Scientist at the van der Paul Laboratory, University of Amsterdam, The Netherlands, in 1992, and participated in the Ph.D. student exchange program at the University of Munich, Germany, in 1993. From 1994 to 1996, he was a Post-Doctoral Fellow at Colorado State University, Fort Collins, engaged in work on MO MBE growth and characterization of blue–green semiconductor lasers. In 1996 he joined APA Optics Inc., where he was a Key Researcher in the development of high power AlGaN/GaN transistors and visible-solar blind photodetectors. In 1997, he joined EMCORE Corporation, Somerset, NJ, were he was engaged in the development of the high brightness LEDs and MOCVD reactor design. Since 1998, he has been a Senior Staff Scientist and then a Manager of the wide bandgap materials and devices group at Corning Applied Technologies Corporation, Woburn, MA. His interest is in wide bandgap semiconductor materials and devices. He has published over 50 scientific papers.

Vladimir N. Fuflyigin received the M.S. degree in inorganic chemistry in 1991 and the Ph.D. degree in chemistry of solids in 1995 from Moscow State University, Russia.

From 1993 to 1994, he was with the Technical University of Braunschweig, Germany, as a Visiting Scientist in the framework of a DAAD (Deutsche Akademische Austaschdienst) scholarship. In 1995 he joined Corning Applied Technologies (formerly NZ Applied Technologies), Woburn, MA, as a Staff Scientist and later Senior Staff Scientist, where he was working on electro–optic and pyroelectric materials. His research current interests include synthesis of oxide and III–V semiconductor films, chemical processing of thin films of oxide and semiconductor materials, and integration of ferroelectric oxides with III–V semiconductors.

John W. Graff received the B.S. degree in physics from Case Western Reserve University, Cleveland, OH, in 1997 and is currently pursuing the Ph.D. degree in the Department of Electrical and Computer Engineering, Boston University, Boston, MA. His graduate work involves GaN-based electronic devices.

E. Fred Schubert (F’00) received the Ph.D. degree from the University of Stuttgart, Germany, in 1986.

He is Professor of electrical and computer engineering at Boston University, Boston, MA. He previously served on the scientific staff of AT&T Bell Laboratories and the Max Planck Institute for Solid State Research, Stuttgart, Germany. He is the author of *Doping in III-V Semiconductors* (Cambridge, U.K.: Cambridge University Press, 1993), which was awarded the 1994 Literature Prize of the Verein Deutscher Elektrotechniker (VDE). He has edited other works , has published more than 140 scientific articles, and holds, singly or jointly, 27 patents.

Dr. Schubert was elected a Fellow of the SPIE and is a member of the American Physical Society, the Optical Society of America, and the Material Research Society.