

4-30-2001

## Very-Low-Specific-Resistance Pd/Ag/Au/Ti/Au Alloyed Ohmic Contact to p GaN for High-Current Devices

V. Adivarahan

A. Lunev

M. Asif Khan

J. Yang

Grigory Simin

University of South Carolina - Columbia, [simin@engr.sc.edu](mailto:simin@engr.sc.edu)

*See next page for additional authors*

Follow this and additional works at: [https://scholarcommons.sc.edu/elct\\_facpub](https://scholarcommons.sc.edu/elct_facpub)



Part of the [Electromagnetics and Photonics Commons](#), and the [Electronic Devices and Semiconductor Manufacturing Commons](#)

---

### Publication Info

Published in *Applied Physics Letters*, Volume 78, Issue 18, 2001, pages 2781-2783.

©Applied Physics Letters 2001, American Institute of Physics (AIP).

Adivarahan, V., Lunev, A., Khan, M. A., Yang, J., Simin, G., Shur, M. S., & Gaska, R. (30 April 2001). Very-Low-Specific-Resistance Pd/Ag/Au/Ti/Au Alloyed Ohmic Contact to p GaN for High-Current Devices. *Applied Physics Letters*, 78 (18), 2781-2783. <http://dx.doi.org/10.1063/1.1353813>

This Article is brought to you by the Electrical Engineering, Department of at Scholar Commons. It has been accepted for inclusion in Faculty Publications by an authorized administrator of Scholar Commons. For more information, please contact [digres@mailbox.sc.edu](mailto:digres@mailbox.sc.edu).

---

**Author(s)**

V. Adivarahan, A. Lunev, M. Asif Khan, J. Yang, Grigory Simin, M. S. Shur, and R. Gaska

## Very-low-specific-resistance Pd/Ag/Au/Ti/Au alloyed ohmic contact to p GaN for high-current devices

V. Adivarahan, A. Lunev, M. Asif Khan, J. Yang, G. Simin, M. S. Shur, and R. Gaska

Citation: *Applied Physics Letters* **78**, 2781 (2001); doi: 10.1063/1.1353813

View online: <http://dx.doi.org/10.1063/1.1353813>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/78/18?ver=pdfcov>

Published by the *AIP Publishing*

### Articles you may be interested in

Thermal stability improvement by using Pd/NiO/Al/Ti/Au reflective ohmic contacts to p -GaN for flip-chip ultraviolet light-emitting diodes

Appl. Phys. Lett. **88**, 062113 (2006); 10.1063/1.2173245

Annealing temperature dependence of contact resistance and stability for Ti/Al/Pt/Au ohmic contacts to bulk n-ZnO

J. Vac. Sci. Technol. B **21**, 2378 (2003); 10.1116/1.1621651

Temperature and doping-dependent resistivity of Ti/Au/Pd/Au multilayer ohmic contact to n-GaN

J. Appl. Phys. **91**, 9218 (2002); 10.1063/1.1471390

Electrical characterization, metallurgical investigation, and thermal stability studies of (Pd, Ti, Au)-based ohmic contacts

J. Appl. Phys. **87**, 2437 (2000); 10.1063/1.372198

Microstructural and electrical investigation of Pd/Ge/Ti/Au ohmic contact to pseudomorphic high electron mobility transistor with undoped cap layer

J. Appl. Phys. **84**, 911 (1998); 10.1063/1.368155

### High-Voltage Amplifiers

- Voltage Range from  $\pm 50\text{V}$  to  $\pm 60\text{kV}$
- Current to 25A

### Electrostatic Voltmeters

- Contacting & Non-contacting
- Sensitive to 1mV
- Measure to 20kV



ENABLING RESEARCH AND  
INNOVATION IN DIELECTRICS,  
ELECTROSTATICS,  
MATERIALS, PLASMAS AND PIEZOS



[www.trekinc.com](http://www.trekinc.com)

TREK, INC. 190 Walnut Street, Lockport, NY 14094 USA • Toll Free in USA 1-800-FOR-TREK • (t):716-438-7555 • (f):716-201-1804 • [sales@trekinc.com](mailto:sales@trekinc.com)

# Very-low-specific-resistance Pd/Ag/Au/Ti/Au alloyed ohmic contact to *p* GaN for high-current devices

V. Adivarahan, A. Lunev, M. Asif Khan,<sup>a)</sup> J. Yang, and G. Simin<sup>b)</sup>

*Department of Electrical and Computer Engineering, University of South Carolina, Columbia, South Carolina 29028*

M. S. Shur and R. Gaska

*SET Incorporated, Latham, New York 12110*

(Received 29 November 2000; accepted for publication 12 January 2001)

We report on Pd/Ag/Au/Ti/Au alloyed metallic contact to *p* GaN. An 800 °C anneal for 1 min in flowing nitrogen ambient produces an excellent ohmic contact with a specific contact resistivity close to  $1 \times 10^{-6} \Omega \text{ cm}^2$  and with good stability under high current operation conditions. This high-temperature anneal forms an alloy between Ag, Au, and *p* GaN resulting in a highly *p*-doped region at the interface. Using x-ray photoelectron spectroscopy and x-ray diffraction analysis, we confirm that the contact formation mechanism is the metal intermixing and alloying with the semiconductor. © 2001 American Institute of Physics. [DOI: 10.1063/1.1353813]

The development of low-specific resistance and high-current carrying capability ohmic contacts to Mg doped *p* GaN are one of the major challenges for the high power III–V nitride light emitting diodes (LEDs), laser diodes, bipolar junction transistors, and heterojunction bipolar transistors. A relatively low *p* doping ( $< 1 \times 10^{18} \text{ cm}^{-3}$ ) in *p* GaN, achievable either by metalorganic chemical vapor deposition (MOCVD) or molecular beam epitaxy makes it very difficult to form such *p*-ohmic contacts. To date, best *p*-contact resistivity of  $4 \times 10^{-6} \Omega \text{ cm}^2$  has been reported using Ni/Au<sup>1,2</sup> and Pd/Au<sup>3,4</sup> with oxygen annealing. In the past, several other metal combinations, such as Au,<sup>5,6</sup> Ni,<sup>7,8</sup> Pd,<sup>9</sup> Pt,<sup>7,10</sup> Ni/Au,<sup>10–14</sup> and Pt/Ni/Au,<sup>15,16</sup> have also been studied. Lee and co-workers<sup>4</sup> reported on the surface treatment using boiling aquaregia. This oxidation–reduction reaction, widely used in GaAs technology, improved the contact resistivity by two orders of magnitude to approximately  $4.3 \times 10^{-4} \Omega \text{ cm}^2$ . Nearly all the contact schemes reported to date, employ annealing temperatures in the 450–500 °C range. This low-temperature annealing precludes any melting of the contact metals and prevents the reaction of this metallic alloy with the surface of *p* GaN.

In this letter, we report on Pd/Ag/Au/Ti/Au contact to *p* GaN fabricated using an 800 °C anneal in nitrogen ambient. This high temperature anneal results in the formation of an alloy of Ag and Au, which, in turn, reacts with the top *p*-GaN surface forming a *p*<sup>+</sup> region at the metal–semiconductor interface. Consequently, the resulting *p*-ohmic contact has greatly improved temperature stability, a significantly smaller metal spreading resistance, and superior ohmic characteristics. Using this Pd/Ag/Au/Ti/Au contact scheme, we measure a specific contact resistivity as low as  $1.1 \times 10^{-6} \Omega \text{ cm}^2$ . Our reported *p* contact is similar in nature to the high-temperature annealed (anneal temperature >850 °C). Ti/Al contacts to *n* GaN and *n* AlGaIn, where the metal and semiconductor are shown to react and form

Al<sub>3</sub>TiN<sup>17</sup> and various other<sup>18,19</sup> complexes. These complexes produce an interfacial *n*<sup>+</sup> layer with high *n*-type doping, thereby assisting in the formation of the *n*-ohmic contact. In this letter, we also demonstrate the stability of our Pd/Ag/Au/Ti/Au metallic contact under high-current operation by using it for a vertically conducting GaN–InGaIn multiple quantum well (MQW) LED structure grown on a SiC substrate.

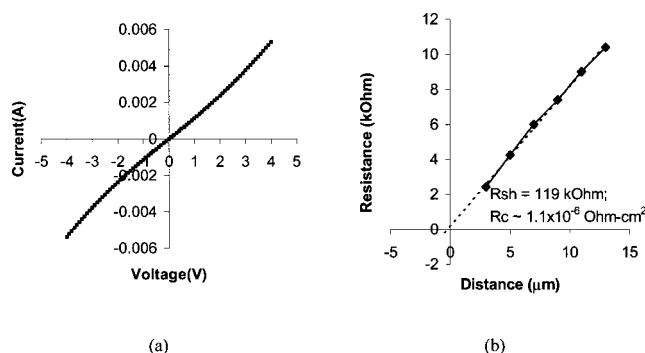
The *p*-GaN films used in this study were grown by low-pressure MOCVD on (0001) sapphire substrate. Trimethylaluminum, Triethylgallium, Bis-cyclopentadienylmagnesium, and Ammonia were used as Al, Ga, Mg, and N source materials, respectively. Hydrogen was used as a carrier gas. Firstly, a 250 Å thick AlN buffer layer was grown at 600 °C, followed by a 1 μm thick undoped highly insulating GaN layer grown at 1000 °C and 76 Torr. Finally, a 0.3 μm micron thick Mg-doped GaN layer was grown and activated by a 750 °C 20 min anneal in N<sub>2</sub> ambient. Room temperature Hall measurements show the hole concentration of  $6 \times 10^{17} \text{ cm}^{-3}$  and the resistivity of 2 Ω cm.

Pd (1 nm)/Ag(50 nm)/Au (10 nm)/Ti (30 nm)/Au (20 nm) contacts were then deposited in a transmission line model (TLM) pattern using *e*-beam evaporation and standard photolithographic lift-off technique. The TLM contact pad size was 50 μm × 150 μm, and the gap between the pads varied from 2 to 14 μm. These *p* contacts were then annealed at a temperature of 800 °C for 1 min in nitrogen ambient using a rapid thermal annealing system. The selection of our contact metals and the high temperature anneal is based on the realization that Ag and Au form an alloy at a temperature of about 773 °C.<sup>20,21</sup> This temperature is also close to the temperature required for *p*-GaN activation and is less than the upper limit at which the optical emission characteristics of InGaIn/GaN MQW degrade. The Pd layer in our contacting scheme was included to improve the adhesion of the Ag layer to the surface of *p* GaN.

The current–voltage (*I*–*V*) characteristics were measured between the two TLM contact pads separated by a 2 μm gap. As seen from Fig. 1(a), the contacts were linear

<sup>a)</sup>Electronic mail: asif@enr.sc.edu

<sup>b)</sup>Electronic mail: simin@enr.sc.edu

FIG. 1.  $I$ - $V$  curve (a) and TLM plot (b) for annealed Pd/Ag/Au contact.

even at voltages below 1 V, thus proving the absence of a Schottky barrier at the metal-semiconductor interface. Figure 1(b) shows the resistance between contact pads as a function of the spacing. From these TLM data, we calculated the specific contact resistance to be about  $1 \times 10^{-6} \Omega \text{ cm}^2$ . (A high sheet resistance of  $p$  layer, which is of the order of 100  $\text{k}\Omega$  makes it difficult to determine these low contact resistances with a very high degree of accuracy.)

In order to study the contact formation mechanism, we performed an x-ray photoelectron spectroscopy (XPS) analysis of our samples. The results of this XPS study are depicted in Fig. 2. Figures 2(a) and 2(b) show the profiles of Pd, Ag, Au, and Ti layers before and after the 800 °C anneal, respectively. It is clearly observed that the 800 °C anneal results in

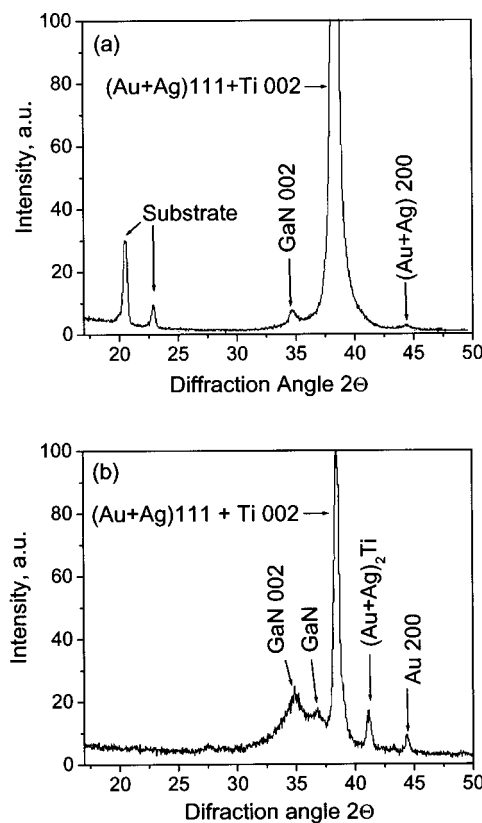


FIG. 3. XRD data of as-deposited (a) and annealed (b) contact.

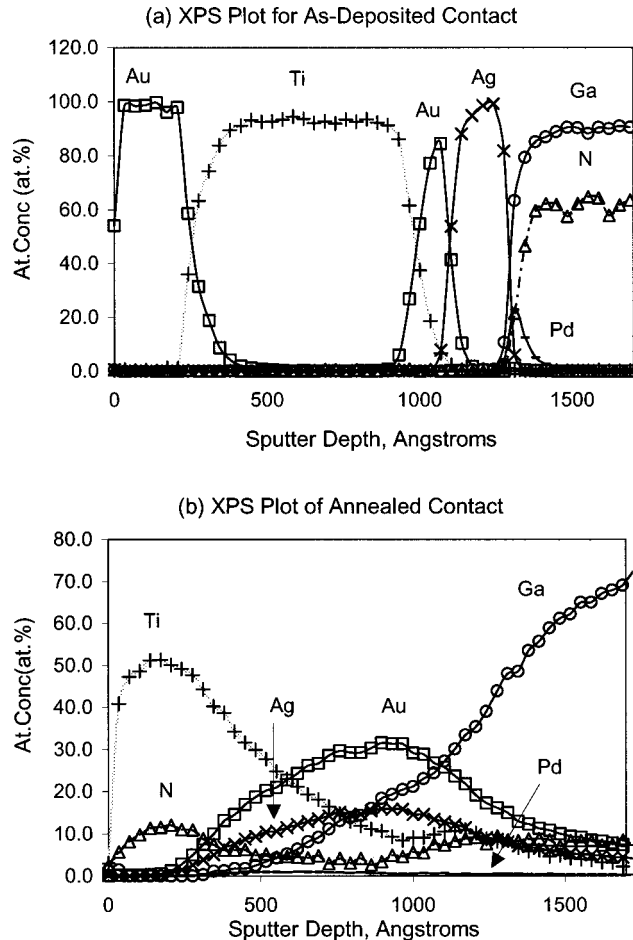


FIG. 2. XPS plot of as-deposited (a) and annealed (b) atomic concentration vs sample sputter depth for Pd/Ag/Au/Ti/Au contact.

an extensive intermixing of the various metals. Further, as seen from Fig. 2(b), after the anneal, Ag, and Au layers have nearly identical profiles of concentration distribution indicating an alloy formation adjacent to the GaN surface. The data of Fig. 2(b) also show that an intensive interpenetration of the (Ag/Au) alloy into  $p$  GaN has taken place. We thus speculate that the ohmic behavior of our contact results from the alloy formation between these two metals (Ag and Au) and from the alloy interpenetration into the top surface of the  $p$  GaN. According to the binary phase diagram,<sup>20,21</sup> two intercalation compounds, namely,  $\text{Me}_2\text{GaN}$  and  $\text{Me}_3\text{GaN}$  for  $\text{Me-Ga-N}$  ( $\text{Me}=\text{Metal}$ ) metal-semiconductor interface can be formed. However, only  $\text{Me}_2\text{GaN}$  compound is chemically stable. Our 800 °C anneal should therefore yield a complex compound of  $(\text{Ag+Au})_2\text{GaN}$ , which, we believe, creates a highly doped  $p^+$  region at the metal and  $p$  GaN interface.

In order to further confirm these XPS results and the suggested contact formation mechanism, we performed an x-ray diffraction (XRD) analysis. Figure 3(a) shows the XRD data for the as-deposited sample and Fig. 3(b) includes the XRD data after the 800 °C anneal. As seen, the (002) GaN peak has broadened out in the annealed sample indicating that the top surface of GaN is disordered by the Au/Ag diffusion. This result agrees with the XPS data discussed. However, the exact nature of the compound, which acts as creating shallow acceptors, needs further investigations.

To further confirm the (Au/Ag) interpenetration into GaN, we removed the annealed contact by boiling it in aquaregia followed by an hydrogen fluoride dip. Small pits with the same dimensions as the contact pad were observed having a depth of approximately 200–250 Å.

In order to prove the feasibility of using our Pd/Ag/Au/



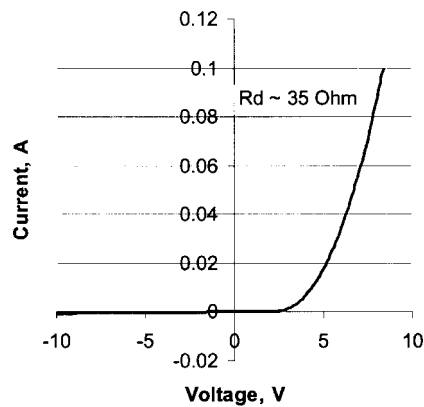


FIG. 4. dc current-voltage characteristic of  $2\text{ }\mu\text{m}\times 700\text{ }\mu\text{m}$  stripe-geometry MQW LED with Pd/Ag/Au contact. (0.1 A dc current corresponds to device current density of  $7.1\text{ kA/cm}^2$ .)

Ti/Au contact in high-current devices, we used such  $p$  contact in a vertically conducting InGaN/GaN MQW LED structure grown on SiC. The epilayer structure for this MQW LED was deposited over  $n^+$  SiC substrates using low-pressure MOCVD. It consisted of a  $0.1\text{ }\mu\text{m}$  thick  $n^+$ -AlGaIn buffer layer, a  $0.2\text{ }\mu\text{m}$  thick Si doped  $n^+$ -GaIn layer ( $n^+ \sim 1 \times 10^{18}\text{ cm}^{-3}$ ), a  $500\text{ }\text{\AA}$  thick  $n$ -GaIn layer ( $n = 5 \times 10^{17}\text{ cm}^{-3}$ ), an InGaIn/GaN MQW and a  $0.15\text{ }\mu\text{m}$  thick  $p$ -GaIn ( $p = 5 \times 10^{17}\text{ cm}^{-3}$ ) cap layer. The MQW region consisted of four  $30\text{ }\text{\AA}$  thick  $\text{In}_{0.22}\text{Ga}_{0.78}\text{N}$  quantum wells surrounded by  $30\text{ }\text{\AA}$  thick GaIn barrier layers.

The LED devices were fabricated by first forming a flat  $n$  contact to the  $n^+$  SiC substrate using Ni ( $50\text{ }\text{\AA}$ )/Al ( $100\text{ }\text{\AA}$ )/Ti ( $200\text{ }\text{\AA}$ )/Au ( $1000\text{ }\text{\AA}$ ). The  $n$  contact was annealed at  $850^\circ\text{C}$  for 1 min. Finally, stripe-geometry ( $2\text{ }\mu\text{m} \times 700\text{ }\mu\text{m}$ ) Pd/Ag/Au/Ti/Au  $p$ -ohmic contacts were formed on the top of the  $p$  layer using the described procedure. Figure 4 shows the  $I$ - $V$  characteristics of this stripe-geometry MQW LED under dc pumping. As seen from Fig. 4, the Pd/Ag/Au/Ti/Au contacts can easily support the current density as high as  $7\text{ kA/cm}^2$ . No contact degradation was observed for this high-current operation. The device shown in Fig. 4 demonstrated stable emission with the peak emission wavelength  $\lambda_p = 410\text{ nm}$  and a full width at half maximum of  $12\text{ nm}$ .

In summary, we report on Pd/Ag/Au/Ti/Au ohmic contact to  $p$  GaIn. Using a 1 min  $800^\circ\text{C}$  anneal in  $\text{N}_2$  ambient, the contact resistivity as low as  $1 \times 10^{-6}\text{ }\Omega\text{ cm}^2$  was achieved. XPS and XRD data are presented to establish the contact formation mechanism, which was forming an Ag/Au

alloy with its subsequent interpenetration into the  $p$ -GaIn surface region. We also demonstrate the stability of our new Pd/Ag/Au/Ti/Au contact under high-current operation by using this contact for a  $pn$ -junction InGaIn/GaN MQW LED operating at current densities as high as  $7.1\text{ kA/cm}^2$ .

The work at USC was supported by the Ballistic Missile Defense Organization (BMDO) under Army SMDC Contract No. DASG60-98-1-0004, monitored by Mr. Tarry Bauer, Dr. Brian Strickland, and Dr. Kepi Wu.

- <sup>1</sup>J. K. Shen, Y. K. Su, G. C. Chi, P. L. Koh, M. J. Jou, C. M. Chang, C. C. Liu, and W. C. Hung, Appl. Phys. Lett. **74**, 2340 (1999).
- <sup>2</sup>J.-K. Ho, C.-S. Jong, C. C. Chiu, C.-N. Huang, C.-Y. Chen, and K.-K. Shih, Appl. Phys. Lett. **74**, 1275 (1999).
- <sup>3</sup>J.-K. Kim, T.-L. Lee, J. W. Lee, H. E. Shin, Y. J. Park, and T. Kim, Appl. Phys. Lett. **73**, 2953 (1998).
- <sup>4</sup>J.-L. Lee, M. Weber, J. K. Kim, J. W. Lee, Y. J. Park, T. Kim, and K. Lymn, Appl. Phys. Lett. **74**, 2289 (1999).
- <sup>5</sup>T. Mori, T. Kozawa, T. Ohwaki, Y. Taga, S. Nagai, S. Yamasaki, S. Asami, N. Shibata, and M. Koike, Appl. Phys. Lett. **69**, 3537 (1996).
- <sup>6</sup>L. L. Smith, R. F. Davis, M. J. Kim, R. W. Carpenter, and Y. Huang, J. Mater. Res. **12**, 2249 (1997).
- <sup>7</sup>K. V. Vassilevski, M. G. Rastegaeva, A. I. Babanin, I. P. Nikitina, and V. A. Dmitriev, MRS Internet J. Nitride Semicond. Res. **1**, 38 (1996).
- <sup>8</sup>Y. Yamaoka, Y. Kaneko, S. Nakagawa, and N. Yamada, Proceedings of the Second International Conference on Nitride Semiconductors, Tokushima, Japan, 27–31 October 1997, pp. 1–19.
- <sup>9</sup>D. J. King, L. Zhang, J. C. Ramer, S. D. Hersee, and L. F. Lester, Mater. Res. Soc. Symp. Proc. **468**, 421 (1997).
- <sup>10</sup>T. Kim, M. C. Yoo, and T. Kim, Mater. Res. Soc. Symp. Proc. **449**, 1061 (1997).
- <sup>11</sup>H. Ishikawa, S. Kobayashi, Y. Koide, S. Yamasaki, S. Nagai, J. Umezaki, M. Koike, and M. Murakami, J. Appl. Phys. **81**, 1315 (1997).
- <sup>12</sup>J. T. Trexler, S. J. Pearton, P. H. Holloway, M. G. Mier, K. R. Evans, and R. F. Karlicek, Mater. Res. Soc. Symp. Proc. **449**, 1091 (1997).
- <sup>13</sup>T. Kim, J. Khim, S. Chae, and T. Kim, Mater. Res. Soc. Symp. Proc. **468**, 427 (1997).
- <sup>14</sup>J. K. Sheu, Y. K. Su, G. C. Chi, P. L. Koh, M. J. Jou, C. M. Chang, C. C. Liu, and W. C. Hung, Appl. Phys. Lett. **74**, 2340 (1999).
- <sup>15</sup>J.-S. Jang, I.-S. Cheng, H.-K. Kim, T.-Y. Seong, S. H. Lee, and S. J. Park, Appl. Phys. Lett. **74**, 70 (1999).
- <sup>16</sup>J.-S. Jang, K.-H. Park, H.-K. Jang, H.-G. Kim, and S.-J. Park, J. Vac. Sci. Technol. B **16**, 3105 (1998).
- <sup>17</sup>S. Ruvimov, Z. L. Weber, J. Washburn, K. J. Duxstad, E. E. Haller, Z. F. Fan, S. N. Mohammad, W. Kim, A. E. Botchkarev, and H. Morkoç, Appl. Phys. Lett. **69**, 1556 (1996).
- <sup>18</sup>S. Ruvimov, Z. L. Weber, J. Washburn, D. Qiao, S. S. Lau, and P. K. Chu, Appl. Phys. Lett. **73**, 2582 (1998).
- <sup>19</sup>B. P. Luther, S. E. Mohny, T. N. Jackson, M. A. Khan, Q. Chen, and J. W. Yang, Appl. Phys. Lett. **70**, 57 (1997).
- <sup>20</sup>Binary Alloy Phase Diagrams, edited by T. Massalsky (American Society for Metals, Metals Park, OH, 1990).
- <sup>21</sup>Handbook of Ternary Alloy Phase Diagrams, edited by P. Villars, A. Prince, and H. Okamoto (American Society for Metals, Metals Park, OH, 1995).