Sb-mediated growth of n- and p-type AlGaAs by molecular beam epitaxy

S. R. Johnson, Yu. G. Sadofyev, D. Ding, Y. Cao, S. A. Chaparro, K. Franzreb, and Y.-H. Zhang

Citation: *Journal of Vacuum Science & Technology B* **22**, 1436 (2004); doi: 10.1116/1.1705579

View online: <http://dx.doi.org/10.1116/1.1705579>

View Table of Contents: <http://scitation.aip.org/content/avs/journal/jvstb/22/3?ver=pdfcov>

Published by the AVS: Science & Technology of Materials, Interfaces, and Processing

Articles you may be interested in

[Molecular beam epitaxy growth of high electron mobility InAs/AlSb deep quantum well structure](#)

J. Appl. Phys. **114**, 013704 (2013); 10.1063/1.4811443

[Structural, morphological, and defect properties of metamorphic In_{0.7}Ga_{0.3}As/GaAs_{0.35}Sb_{0.65} p-type tunnel field effect transistor structure grown by molecular beam epitaxy](#)

J. Vac. Sci. Technol. B **31**, 041203 (2013); 10.1116/1.4812793

[Sb surfactant effect on GaInAs/GaAs highly strained quantum well lasers emitting at 1200 nm range grown by molecular beam epitaxy](#)

J. Appl. Phys. **96**, 44 (2004); 10.1063/1.1760841

[Sb-mediated growth of Si-doped AlGaAs by molecular-beam epitaxy](#)

Appl. Phys. Lett. **84**, 3546 (2004); 10.1063/1.1715153

[Si doping for n- and p-type conduction in Al_xGa_{1-x}As grown on GaAs\(311\)A by molecular-beam epitaxy](#)

J. Appl. Phys. **93**, 2638 (2003); 10.1063/1.1539912

SHIMADZU Excellence in Science

Powerful, Multi-functional UV-Vis-NIR and FTIR Spectrophotometers

Providing the utmost in sensitivity, accuracy and resolution for applications in materials characterization and nano research

- Photovoltaics
- Polymers
- Thin films
- Paints
- Ceramics
- DNA film structures
- Coatings
- Packaging materials

[Click here to learn more](#)

Sb-mediated growth of *n*- and *p*-type AlGaAs by molecular beam epitaxy

S. R. Johnson,^{a)} Yu. G. Sadofyev, D. Ding, Y. Cao, S. A. Chaparro, K. Franzreb, and Y.-H. Zhang

Center for Solid State Electronics Research and Department of Electrical Engineering,
Arizona State University, Tempe, Arizona 85287-6206

(Received 27 October 2003; accepted 24 February 2004; published 7 June 2004)

The Sb-mediated growth of $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ is studied for Sb/III flux ratios from 0% to 2% and growth temperatures from 580 to 720 °C. The surface morphology and electrical properties are found to strongly depend on both the growth temperature and Sb flux. As an isoelectronic dopant, Sb improves the conductivity of *n*- $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ and reduces the conductivity of *p*- $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$. As a surfactant, Sb improves the surface morphology of $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ at all growth temperatures with the most dramatic improvement occurring at 670 °C. The smoothest surface (0.2 nm root-mean-square roughness height) was obtained at 700 °C using a Sb/III flux ratio of 0.02. This work demonstrates that Sb-mediated molecular beam epitaxy growth of *n*-AlGaAs effectively eliminates the “forbidden temperature gap” for device quality *n*-AlGaAs. © 2004 American Vacuum Society. [DOI: 10.1116/1.1705579]

I. INTRODUCTION

Today, molecular beam epitaxy (MBE) is widely used to grow optoelectronic devices, such as, in-plane lasers and vertical cavity surface emitting lasers (VCSELs) that cover wavelength ranges from visible to near infrared. These devices typically require a significant amount of Al containing alloys to achieve low index optical confinement layers and high band gap carrier confinement layers. AlGaAs as a nearly lattice-matched alloy, in particular, is widely used on the GaAs substrate, making it the material of choice for GaAs based lasers. Due to the wide range of temperatures required for active materials, such as GaAs, InGaAs, and GaAsSb, it is important that high quality AlGaAs growth is accessible over a wide range of substrate temperatures. Furthermore, good control of surface morphology and deposition rate is important for VCSELs, since accurate layer thickness and smooth interfaces are critical to good device performance.

The existence of a forbidden substrate temperature gap for the growth of AlGaAs layers by MBE has been widely reported.^{1–4} The surface morphology of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x > 0.2$) is smooth for lower growth temperatures (550–600 °C), rough for intermediate temperatures (620–680 °C), and smooth for high temperatures (700–750 °C). These temperature ranges may vary slightly with the Al composition. The lower growth temperatures result in epitaxial layers with smooth surface morphology that have less than optimal electrical properties compared to layers grown at higher temperatures. At the highest growth temperatures the sticking coefficient of Ga is less than unity and strongly dependent on the growth temperature, resulting in poor layer composition and thickness control. Therefore, compromises are typical when choosing adequate growth temperatures for GaAs/AlGaAs distributed Bragg reflectors in VCSEL devices.

Sb as a surfactant has been proposed⁵ for the growth of

smoother AlGaAs in the forbidden temperature gap where the Ga sticking coefficient is close to unity and the Sb incorporation rate is close to zero. Since most device applications require a substantial Al mole fraction, we chose to study the Sb-mediated growth of Si and Be doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layers with emphasis on optimizing the electrical properties in addition to the more widely studied surface properties.

II. EXPERIMENTAL RESULTS

A set of Si doped ($N_{\text{Si}} = 2.0 \times 10^{18} \text{ cm}^{-3}$) $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ samples were grown at various temperatures (580, 610, 640, 670, 700, and 720 °C) and various Sb/III flux ratios (0.00, 0.005, 0.01, and 0.02). In addition to the extensive set of *n*-type samples, several Be doped ($N_{\text{Be}} = 2.0 \times 10^{18} \text{ cm}^{-3}$) $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ samples were grown at 580 and 640 °C with Sb/III flux ratios of 0.00 and 0.02. The growth was done using a V80H VG solid source MBE system equipped with Ga, Al, Si, and Be effusion cells and As and Sb valved crackers. The As and Sb cracking zones were operated at 1000 °C to ensure that the group-V species were cracked. The samples were grown on semi-insulating GaAs (001) substrates starting with a 30 nm undoped GaAs buffer layer, followed by a 200 nm thick undoped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ spacer layer and a 1000 nm thick Si (or Be) doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layer. The undoped spacer provides a barrier to free carrier penetration, thus eliminating the possible formation of a two-dimensional electron gas in the GaAs buffer layer that could have an adverse effect on electrical measurements of the samples. Finally, the doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layer was capped with a thin 10 nm Si (or Be) doped GaAs contact layer, whose thickness was chosen to be thick enough to provide electrical contact and yet thin enough not to obscure the surface morphology or conductivity of the underlying AlGaAs layer.

The group-V flux values are given in absolute terms, with $\text{Sb/III} = \text{Sb}/(\text{Ga} + \text{Al})$, where, for example, the flux of each element is in units of incident atoms per unit area per unit time. The $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layers are random alloy and were

^{a)}Author to whom correspondence should be addressed; electronic mail: shane.johnson@asu.edu

FIG. 1. Surface morphology of 1.2 μm thick Si doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layers grown at various Sb/III flux ratios and substrate temperatures. (a) Length scale of the surface roughness in the $[110]$ direction. (b) rms height of the surface roughness.

grown under a group-V stabilized 2×4 surface reconstructed for both Sb-mediated and Sb-free growth. The As_2 overpressure was varied depending on the growth temperature, with $\text{As}/\text{III}=1.5$ at 580, 610, and 640 °C, $\text{As}/\text{III}=1.8$ at 670 °C, and $\text{As}/\text{III}=2.0$ at 700 and 720 °C. The absolute V/III flux ratios were established using the onset of the Ga rich surface reconstruction (or Ga droplet formation) to find the one-to-one flux ratio ($\text{Sb}/\text{Ga}=1.0$ or $\text{As}/\text{Ga}=1.0$), from which each group-V flux curve was normalized in absolute terms. The growth (substrate) temperatures were accurately measured by means of the substrate band edge using diffuse reflection spectroscopy⁶ and were controlled via a substrate thermocouple which was typically about 100 °C higher than the substrate temperature. The samples were investigated using atomic force microscopy (AFM), x-ray diffraction (XRD), secondary ion mass spectroscopy (SIMS), and Hall effect measurements in the van der Pauw contact geometry.

The surface morphology of each sample was examined by AFM. The length scale of the roughness in the $[110]$ direction, $L_{[110]}$, and the root mean square (rms) height of the surface roughness obtained from these measurements is reported in Fig. 1 for the various Sb fluxes and growth temperatures. Note that both the sample grown at 580 °C with $\text{Sb}/\text{III}=0.005$ and the sample grown at 700 °C with $\text{Sb}/\text{III}=0.00$ exhibit two length scales, as shown in Fig. 1(a). The length scales were ascertained through two-dimensional (2D) fast Fourier transform (FFT) analysis of the AFM images and only observed in the $[110]$ direction. The $L_{[110]}$ length scales

are a result of surface trenches and ridges orientated perpendicular to, and periodic in, the $[110]$ direction.

The smoothing effect of the Sb surfactant in the forbidden temperature gap is evident and the amount of Sb flux required for smoothing tends to increase with the substrate temperature. A Sb/III flux ratio of 0.005 is sufficient for substrate temperatures below 620 °C, whereas a Sb/III flux ratio of 0.01 to 0.02 is necessary in the forbidden temperature gap. The length scale of the roughness in the forbidden temperature gap is insensitive to the Sb/III flux ratio, holding constant at about 200 nm, albeit the rms roughness height is reduced from over 3 to less than 1 nm. On the other hand, the roughness length scale abruptly doubles at 700 °C where higher growth temperatures result in smoother surfaces with rms roughness heights below 1 nm.

To correlate the quantitative roughness shown in Fig. 1 with the qualitative optical characterization that is commonly used to describe the roughness of epitaxial films, the following observations are offered. The smoothest AlGaAs layers (~ 0.2 nm rms roughness) were grown at 700 and 720 °C with a Sb/III flux ratio of 0.02. Remarkably, these surfaces have the same low levels of roughness as high quality MBE grown GaAs and have a flat mirror like appearance under a high-magnification optical microscope (with or without phase contrast) and exhibit no optical scattering under a bright white-light source. For higher rms roughness levels around 0.5 nm the samples show some texture under an optical microscope and appear hazy under a bright light. For surfaces with poor morphology, the rms roughness exceeds 1 nm and the surface texture is clearly visible under an optical microscope and the samples appear hazy under ambient lighting. These optical scattering observations are valid when the roughness length scales are on the order of the wavelengths of visible light, which is typically the case for MBE grown material and the reason why optical scattering is such a common qualitative technique used by MBE growers.

The XRD measurements reveal that about 40% of the incident Sb flux is incorporated at the lowest substrate temperature (580 °C). As the substrate temperature increases the Sb incorporation decreases exponentially, quickly dropping below concentrations measurable by XRD. Therefore to determine the temperature dependence of the Sb sticking coefficient, S_{Sb} (or incorporation), SIMS measurements were done on the samples grown under the highest (0.02) Sb/III flux. The XRD measurements were used to assign absolute numbers to the SIMS data shown in Fig. 2. The Sb sticking coefficient (left-hand axis) and the Sb concentration (right-hand axis) decrease by two orders of magnitude over the temperature range shown, resulting in a low (but nonzero) Sb concentration of about $2\times 10^{18}\text{ cm}^{-3}$ in samples grown at 700 °C. Even at the highest growth temperatures Sb is incorporated as an isoelectronic dopant. The Sb sticking coefficient exhibits an Arrhenius behavior (solid line fit to the data) with characteristic energy 2.76 ± 0.15 eV. The equation with the best-fit parameters is shown in Fig. 2 where kT is in units of absolute temperature. The constant in front of the

FIG. 2. Sb sticking coefficient and codoping concentration in MBE grown $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}:\text{Sb}$ as a function of the substrate temperature for a Sb/III flux ratio of 0.02.

exponential is $4.0 \times 10^{18} \text{ cm}^{-3}$ for the Sb concentration and 1% for the Sb sticking coefficient.

Figure 3 shows the room temperature Hall mobility and resistivity of the Si doped ($N_{\text{Si}} = 2 \times 10^{18} \text{ cm}^{-3}$) $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layers discussed above and shown in Fig. 1. The electron mobility increases with the growth temperature and is enhanced by Sb codoping. Remarkably, at the lower growth temperatures where the Sb codoping levels are large ($\sim 10^{20} \text{ cm}^{-3}$), Sb as an isoelec-

FIG. 3. Electrical properties of $1.0 \mu\text{m}$ thick Si doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layers grown at various Sb/III flux ratios and substrate temperatures. (a) Electron mobility, with the electron concentration and doping efficiency shown in the inset. (b) Sheet resistance and resistivity; the solid lines are fits to the data for samples grown without Sb (upper curve) and with Sb (lower curve).

tronic dopant still improves the electron mobility, indicating that Sb codoping does not add to electron scattering. In the 640 to 670 °C growth temperature range, the optimal Sb codoping level is about $3 \times 10^{18} \text{ cm}^{-3}$ (Sb/III=0.005–0.01). For the highest growth temperature (720 °C), the mobility decreases because the Al mole fraction erroneously increases from 0.65 to 0.70 when the Ga sticking coefficient decreases from close to unity at 700 °C to 0.8 at 720 °C. The Al mole fraction (and hence Ga sticking) is determined from strain measurements of the AlGaAs layer using XRD. At high growth temperatures the contribution of incorporated Sb to strain is roughly equivalent to +1% in Al mole fraction and is disregarded in the Ga sticking coefficient analysis.

Despite the fact that growth temperature and Sb codoping have a dramatic effect on the electron mobility, the overall contribution to the conductivity is not as spectacular because of a strong dependence of the electron concentration (doping efficiency) on the growth temperature, as shown in the inset of Fig. 3(a). The electron concentration is given on the left-hand axis and the Si doping efficiency is given on the right-hand axis. Here the Si doping efficiency is defined as $n_{\text{AlGaAs}}/n_{\text{GaAs}}$ (Hall measurements) for a given Si doping flux; note that we are assuming that $n_{\text{GaAs}} \sim N_{\text{Si}}$, neglecting the fact that a small fraction of Si incorporates as an acceptor in GaAs. Although not as absolutely accurate as Hall measurements, SIMS measurements tend to validate our assumption, where we found that $N_{\text{SIMS}} \sim 7 \times 10^{17} \text{ cm}^{-3}$ for Si-doped GaAs with $n_{\text{GaAs}} = 1 \times 10^{18} \text{ cm}^{-3}$. The accuracy of the SIMS data is limited by the $\pm 40\%$ absolute accuracy of the Si implant samples used as SIMS reference standards.

The trend in doping efficiency, shown by the solid line, Fig. 3(a) inset, is independent of the Sb codoping levels and has a minimum of 10% at 660 °C, right in the heart of the forbidden temperature gap. The best doping efficiency (25%) occurs at the lowest growth temperature (580 °C). Notwithstanding the decline in electron concentration, the conductivity of the AlGaAs layer increases with the growth temperature, as shown by the plot in Fig. 3(b) with resistivity on the right-hand axis and sheet resistance on the left-hand axis. The solid lines are fits to the data from samples grown without Sb (upper curve) and with Sb (lower curve). On average, the sheet resistance decreases at a rate of $-5 \Omega/\text{°C}$ and is further reduced by $120 \Omega/\square$ when Sb codoping is present.

The impact of Sb as an isoelectronic dopant in $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ is presented in Fig. 4 for the various growth temperatures. The Sb levels shown here are calculated using the Sb sticking coefficient given in Fig. 2 and the incident Sb/III flux rates. Note that the smallest Sb concentrations (left-hand side of each curve) are for the samples grown with the Sb source off (Sb/III=0.00), where the unintentional Sb comes from the Sb background in the growth chamber. In this case, the Sb codoping level calculation is based on the typical 10^{18} cm^{-3} Sb background levels observed by SIMS measurements on samples grown at 580 °C. The increase in electron mobility with higher Sb codoping levels is clearly seen in Fig. 4(a). On the other hand, in Fig. 4(b), the electron

FIG. 4. Electrical properties as a function of the Sb codoping concentration for 1.0 μm thick Si doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layers grown at various substrate temperatures. (a) Electron mobility. (b) Electron concentration.

concentration shows no observable dependence on the Sb codoping levels.

The results of the Be doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ samples are summarized in Fig. 5. The rms height of the surface roughness is shown in Fig. 5(a) and is less than 1 nm for all four samples. Of the samples grown at 640 $^{\circ}\text{C}$, the Be doped samples are about three times smoother than the Si doped samples. It is possible that surface segregation of the Be dopant serves as surfactant, resulting in a smoother growth surface at 640 $^{\circ}\text{C}$. The Be doped samples grown at 580 $^{\circ}\text{C}$ do not exhibit a roughness length scale and the samples grown at 640 $^{\circ}\text{C}$ display a length scale around 200 nm in the $[110]$ direction, similar to that observed in the Si doped samples discussed above. The hole mobility and material resistivity of Be doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ are shown in Fig. 5(b). Unlike the Si doped material, the Be doped material does not exhibit a change in doping efficiency with the growth temperature; the doping efficiency is 75% for all four samples. The Be impurity and hole concentrations are listed in Fig. 5(b). Similar to the Si doped samples, the carrier mobility and material resistivity of the Be doped samples increase with the growth temperature, however, unlike the Si doped samples, Sb as a codopant substantially reduces the carrier mobility and material conductivity.

III. DISCUSSION

Sb acts as both a surfactant and an isoelectronic dopant in AlGaAs. As a surfactant, Sb provides improved surface mor-

FIG. 5. Surface morphology (of 1.2 μm thick) and the electrical properties (of 1.0 μm thick) Be doped $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ layers grown at various Sb/III flux ratios and substrate temperatures. (a) rms height and $[110]$ length scale of the surface roughness. (b) Hole mobility and resistivity.

phology with the most dramatic improvement occurring in the forbidden temperature gap. During Sb-mediated growth a steady-state surface population of Sb is maintained, enhancing the surface diffusion kinetics of the Ga and Al adatoms. The three-dimensional morphology of AlGaAs layers grown in the forbidden temperature gap is thought to originate from less than ideal Ga and Al transport caused by oxygen gettering on the surface,⁷ strong anisotropy of surface diffusion,⁸ the strong Al–As bond,⁹ and diffusion barriers at island edges.¹⁰

The anisotropic diffusion at the atomic scale presumably drives the 200 nm length scale roughness observed in the $[110]$ direction. In which case, the group-V terminated dimer rows perpendicular to the $[110]$ direction oppose group-III adatom diffusion in that direction, while the group-III terminated trenches between the dimer rows assist group-III adatom diffusion in the perpendicular $[\bar{1}10]$ direction. At higher temperatures above the forbidden temperature gap, Ga and Al diffusion is enhanced, resulting in smoother films. Below the forbidden temperature gap, surface impurities are thought to be more readily incorporated, interfering less with surface mobility, and the Al adatoms tend to stay put thereby avoiding roughening due to anisotropic diffusion.

Isoelectronic doping reduces deep levels¹¹ which improves the material properties of Si doped AlGaAs where deep-level traps are not simply arsenic or gallium vacancies, but possibly impurities or gallium/arsenic related complexes.¹² Furthermore, isoelectronic doping can reduce unin-

tentional impurities and dislocation density in III–V materials.¹³ As an isoelectronic dopant, Sb yields higher electron mobility and lower sheet resistance in *n*-AlGaAs:Si and lower hole mobility and higher sheet resistance in *p*-AlGaAs:Be. An interesting result given that Sb occupies group-V sites and as *n* and *p* dopants, both Si and Be impurities occupy group-III sites.

The overall doping efficiency of Si in Al_{0.65}Ga_{0.35}As is low because the dominant Si donor level sits well below the conduction band¹⁴ and some of the dopant atoms are likely incorporated as acceptors due to the amphoteric nature of Si. The notable temperature dependence of the doping efficiency may be due to an amphoteric behavior of Si atoms in AlGaAs that depends on the growth temperature or that the Si donor activation depends on the growth temperature. Compensation by defects is another possibility, in which case the defect formation would have to depend only on the temperature and not on the Sb codoping or surface morphology. On the other hand, the doping efficiency of Be in Al_{0.65}Ga_{0.35}As is independent of the growth temperature and Sb codoping.

IV. CONCLUSIONS

Sb-mediated growth improves both the electrical properties and the surface morphology of Si doped Al_{0.65}Ga_{0.35}As; as an isoelectronic dopant Sb increases the electron mobility and as a surfactant Sb reduces surface roughness. The most impressive results occur in the 620–680 °C temperature

range, essentially eliminating the forbidden temperature gap for *n*-AlGaAs:Si growth in devices. Sb-mediated growth improves the surface morphology and degrades the electrical properties of Be doped Al_{0.65}Ga_{0.35}As; as a surfactant Sb reduces surface roughness and as an isoelectronic dopant Sb decreases hole mobility.

- ¹H. Morkoç, T. J. Drummond, W. Kopp, and R. Fischer, *J. Electrochem. Soc.* **129**, 824 (1982).
- ²W. I. Wang, S. Judaprawira, C. E. C. Wood, and L. F. Eastman, *Appl. Phys. Lett.* **38**, 708 (1981).
- ³R. A. Stall, J. Zilko, V. Swaminathan, and N. Schumaker, *J. Vac. Sci. Technol. B* **3**, 524 (1985).
- ⁴L. P. Erickson, T. J. Mattord, W. P. Palmberg, R. Fischer, and H. Morkoç, *Electron. Lett.* **19**, 632 (1983).
- ⁵R. Kaspi, K. R. Evans, D. C. Reynolds, J. Brown, and M. Skowronski, *Mater. Res. Soc. Symp. Proc.* **379**, 79 (1995).
- ⁶S. R. Johnson, C.-H. Kuo, M. D. Boonzaayer, W. Braun, U. Koelle, Y.-H. Zhang, and J. A. Roth, *J. Vac. Sci. Technol. B* **16**, 1502 (1998).
- ⁷N. Chand, S. N. G. Chu, and M. Geva, *Appl. Phys. Lett.* **59**, 2874 (1991).
- ⁸R. Mirin, M. Krishnamurthy, J. Ibbetson, and J. English, and A. Gossard, *J. Cryst. Growth* **127**, 908 (1993).
- ⁹F. Alexandre, L. Goldstein, G. Leroux, M. C. Joncour, H. Thibierge, and E. V. K. Rao, *J. Vac. Sci. Technol. B* **3**, 950 (1985).
- ¹⁰J. M. Van Hove and P. I. Cohen, *Appl. Phys. Lett.* **47**, 726 (1985).
- ¹¹C. E. C. Wood, T. M. Kerr, T. D. McLean, D. I. Westwood, J. D. Medland, S. Bright, and R. Davies, *J. Appl. Phys.* **60**, 1300 (1986).
- ¹²K. D. Jamison, H. C. Chen, A. Bensaoula, W. Lim, L. Trombetta, and A. Ignatiev, *J. Vac. Sci. Technol. A* **7**, 606 (1989).
- ¹³V. K. Bazhenov and V. I. Fistul, *Sov. Phys. Semicond.* **18**, 843 (1984).
- ¹⁴N. Chand, T. Henderson, J. Klem, W. T. Masselink, R. Fischer, Y.-C. Chang, and H. Morkoç, *Phys. Rev. B* **30**, 4481 (1984).