

Transport properties of Be- and Si-doped AlSb

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Thick epitaxial layers of AlSb(Si) and AlSb(Be) were grown by molecular beam epitaxy and characterized by variable-temperature Hall/van der Pauw measurements. Si is shown to be predominantly an acceptor in AlSb, with an energy level 33 ± 4 meV above the top of the valence band. Be is also an acceptor, with an energy level 38 ± 4 meV above the top of the valence band. Be is a robust doping source for *p*-AlSb for carrier densities ranging from 10^{15} to 10^{19} cm⁻³. Background impurity levels in AlSb can be assessed by measuring the transport properties of lightly doped AlSb(Be) layers. © 2000 American Institute of Physics. [S0021-8979(00)00811-2]

I. INTRODUCTION

AlSb is an indirect-gap semiconductor with a room-temperature band gap of 1.69 eV and a lattice constant of 6.136 Å. It is nearly lattice matched to GaSb, InAs, and related alloys. Heterostructures composed of AlSb, GaSb, and InAs are of interest for several electro-optic and electronic device applications. For example, AlSb can serve as a barrier material to confine electrons in InAs-channel high electron mobility transistors¹ or magnetoelectronic hybrid Hall effect devices.² AlSb layers also can function as tunneling barriers in resonant tunneling diodes³ and as barriers in “W” infrared lasers with InAs/InGaSb/InAs active regions.⁴ A few studies of the optical^{5,6} and structural⁷ properties of epitaxial AlSb have been reported. Te has been investigated as an *n*-type dopant in AlSb.⁸ Be has been used as a *p*-type dopant in AlSb for InAs-channel high electron mobility transistors⁹ and InAs/AlSb superlattices.¹⁰ In this article, we investigate the transport properties of Be- and Si-doped AlSb. We determine the acceptor energy levels and demonstrate that Be is a robust doping source for AlSb.

II. EXPERIMENTAL PROCEDURE

Samples were grown by solid-source molecular beam epitaxy (MBE) in a system with conventional In, Ga, Al, Sb, Si, and Be cells as well as an Sb cracking cell and a valved As cracker.¹¹ Growth temperatures were measured by transmission thermometry.¹² Epitaxial layers were grown on semi-insulating (SI) GaAs(001) substrates. Each sample consists of at least 3 μm of AlSb, doped with Si or Be, and a 50 Å GaSb cap to prevent oxidation of the AlSb. The Sb:Al flux ratio was approximately 2:1 for all samples except one (see Sec. III). Most samples were grown near 530 °C; two samples were grown at 600 °C. Unless otherwise noted, the growth rate was 1.0 monolayers/s (1.1 μm/h). The As valve was closed during AlSb growth to minimize As incorporation.

All samples were cleaved into 5×5 mm squares and measured by the conventional Hall/van der Pauw method at room temperature and a field of 2060 G. Selected samples

were also measured as a function of temperature (20–300 K) at a field of 3000 G. Relevant parameters needed to calculate surface and interface band bending are not well known for AlSb. Hence, we ignore depletion effects in our calculations of carrier density from the transport measurements and assume a Hall factor of unity. As a result, the carrier densities reported here could be in error by as much as a factor of two.

III. RESULTS AND DISCUSSION

In Fig. 1, we plot carrier concentration versus Si cell temperature for five Si-doped AlSb films. All samples were *p*-type. Samples A, B, and C were grown during the same growth cycle under nominally identical conditions. Room-temperature mobilities are indicated next to each data point. As expected, carrier concentration increases and mobility decreases as the Si cell temperature (flux) increases. For comparison, we include a dashed line that represents our measurements of Si-doped *n*-GaAs grown in the same MBE system. The AlSb data points all lie more than a factor of two below the GaAs(Si) line. It is well known that Si, a group IV element, is an amphoteric dopant in III–V compounds. The data in Fig. 1 are consistent with more self-compensation in AlSb compared to GaAs. For example, (assuming all impurities are ionized) if 90% of the Si atoms are on Ga sites and 10% on As sites in GaAs, and 30% are on Al sites with 70% on Sb sites in AlSb, then the GaAs will be *n*-type, the AlSb will be *p*-type, and the net carrier concentration, $|N_A - N_D|$, will be a factor of two higher for GaAs.

Variable-temperature transport data for sample B are shown in Fig. 2. Carrier concentration decreases by over three orders of magnitude as temperature decreases from 300 to 30 K, consistent with carrier freeze-out. The solid line is calculated assuming an acceptor concentration, N_A , of 6.5×10^{16} /cm³ with an energy level 33 ± 4 meV above the top of the valence band, and a background donor level, N_D , of 1.5×10^{15} /cm³. The increase in carrier density for $T < 30$ K indicates impurity band conduction.

Two additional samples are indicated in Fig. 1. Sample D was grown in the same growth cycle as A–C. The only difference is that the hot zone of the As cracker was maintained at 875 °C during the AlSb growth for D, compared to

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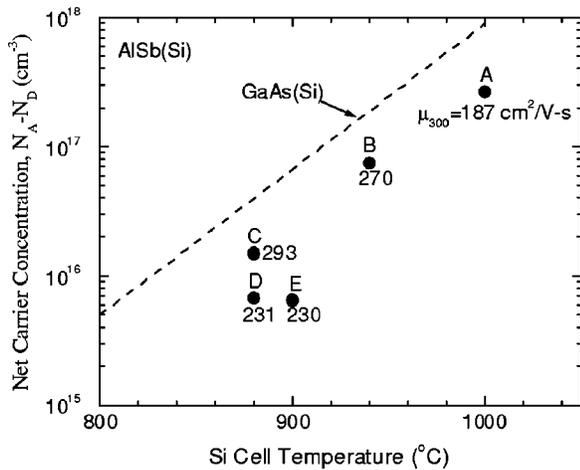


FIG. 1. Net carrier concentration as a function of Si cell temperature for AISb(Si) films. Experimental results for GaAs(Si) are indicated by a dashed line.

400 °C for A–C.¹³ The carrier concentration and mobility of D are lower than C, consistent with incorporation of additional compensating impurities in D. Sample E was grown under the same nominal conditions as A–C but in a later growth cycle, i.e., after a vent of the MBE and recharging of the Al and Sb cells. The carrier concentration and mobility in E suggest that the background impurity levels were higher in the later growth cycle.

Four AISb(Si) samples are not included in Fig. 1 because they were too resistive for valid transport measurements; sheet resistances were more than three orders of magnitude higher than sample D. One of the samples was grown with $T_{Si}=820$ °C. The high resistivity could result from a fully depleted layer, possibly with donor background impurities compensating the Si. Two of the samples, however, were grown with $T_{Si}=910$ °C; one of the two was grown during the same cycle as A–D. A possible explanation is that unintentional variation in growth conditions resulted in nearly equal Si occupancy of Al and Sb sites for these samples. We

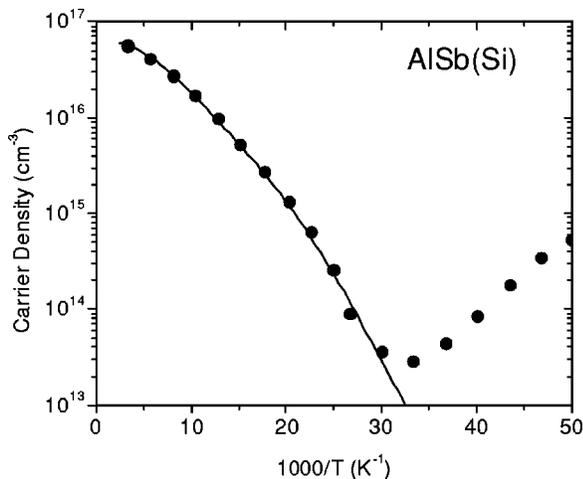


FIG. 2. Net carrier concentration as a function of temperature for sample B, 4- μ m-thick AISb(Si) on Si–GaAs. Solid line is calculated using $N_A=6.5 \times 10^{16}/\text{cm}^3$, $E_A=33$ meV, and $N_D=1.5 \times 10^{15}/\text{cm}^3$.

tried an additional test based upon the early work of Chang *et al.*¹⁴ They achieved *p*-type AISb (10^{15} – $10^{19}/\text{cm}^3$) under normal growth conditions using Ge as a dopant. Under conditions of very high Sb flux, however, Ge was an *n*-type dopant. We grew an AISb sample with an Sb:Al flux ratio of 20:1 and a Si temperature of 888 °C. (The growth rate was 0.2 ML/s; the equivalent 1.0 ML/s Si temperature on Fig. 1 is 920 °C.) The sample was resistive.

Taken as a whole, our AISb(Si) transport results suggest that Si is not a robust doping source for *p*-AISb. The most likely reason is the amphoteric nature of Si, with site selection a sensitive function of growth conditions.

Be, a group II element, can substitute for group III elements and act as an acceptor in arsenides and antimonides. We grew a series of Be-doped AISb layers; all were *p*-type. In Fig. 3, we plot the net carrier concentration as a function of Be cell temperature. For comparison, we include two data points for GaAs(Be) grown in the same MBE system. The net carrier concentrations are similar for AISb(Be) and GaAs(Be), as expected for a nonamphoteric dopant with a unity sticking coefficient. Room-temperature mobilities are indicated next to each data point, and range from 61 $\text{cm}^2/\text{V s}$ for $(N_A - N_D)=1 \times 10^{19}/\text{cm}^3$ to over 300 $\text{cm}^2/\text{V s}$ for samples in the 10^{15} – $10^{16}/\text{cm}^3$ range. The solid curve is a fit to the data using the functional form $ce^{-E_a/kT}$, yielding an activation energy, E_a , of 3.21 eV for the Be cell.

Antimony sources were compared by growing two layers with $T_{Be}=590$ °C. For one, the antimony source was a conventional cell, yielding Sb_4 . For the other, an antimony cracker was employed. The cracker zone temperature was 800 °C, probably resulting in a combination of Sb_2 and Sb_1 .¹⁵ As shown in Fig. 3, the layers have identical carrier concentrations and room-temperature mobilities. We also compared growth temperatures of 530 and 600 °C with $T_{Be}=570$ °C. The mobility and net carrier concentration were higher for the 600 °C sample, suggesting less incorporation of donor impurities.

Variable-temperature transport data for an AISb(Be) sample are shown in Fig. 4. Carrier concentration decreases by nearly six orders of magnitude as temperature decreases from 300 to 25 K, consistent with carrier freeze-out. The solid line is calculated assuming an acceptor concentration, N_A , of $1.3 \times 10^{16}/\text{cm}^3$ with an energy level 38 ± 4 meV above the top of the valence band, and a background donor level, N_D , of $1 \times 10^{15}/\text{cm}^3$. The carrier density is relatively insensitive to temperature for 20 K $< T < 25$ K, indicating the onset of impurity band conduction.

Several articles have explored the role of impurities and native defects in AISb, especially relating to the “doping” of InAs/AISb quantum wells.^{5,16–20} For example, Chadi calculates a donor level 440 meV above the valence-band maximum (VBM) of AISb for the Sb-on-Al antisite (Sb_{Al}).¹⁶ Shen *et al.* proposed that Al_{Sb} could behave as a deep acceptor or deep donor when there are empty states below the Al_{Sb} energy level.¹⁷ Based upon a photoluminescence study of InAs/AISb quantum wells, Fuchs *et al.* postulate an acceptor level 80 meV above the AISb VBM as well as a deep level 420 meV above the AISb VBM.⁵ Our previous work on persistent photoconductivity in InAs/AISb quantum wells sug-

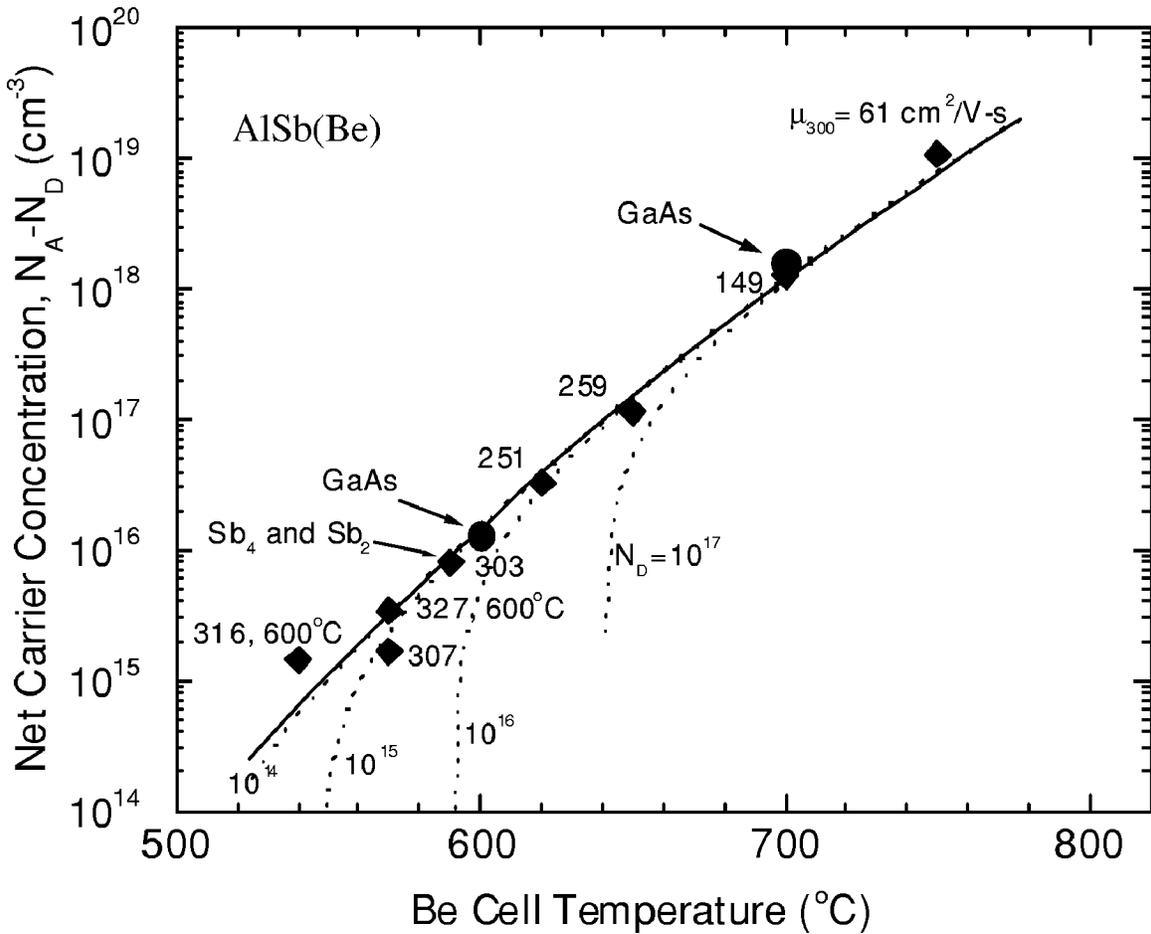


FIG. 3. Net carrier concentration as a function of Be cell temperature for AlSb(Be) films. Two experimental points for GaAs(Si) are included for comparison. Growth temperature was near 530 °C except for two samples at 600 °C. The data point at $T_{\text{Be}} = 570$ °C represents two samples, one using Sb_4 and the other using Sb_2/Sb_1 , with identical carrier concentration and mobility. Solid curve is a fit to $ce^{-E_a/kT}$ with $E_{a,\text{Be}} = 3.21$ eV. Dotted curves simulate different levels of background donors, N_D .

gested the presence of $>4 \times 10^{16}/\text{cm}^3$ deep donors in AlSb, with an energy 410 meV above the AlSb VBM.¹⁸ The presence of deep acceptors should not affect the doping of AlSb by a shallow acceptor such as Be. If, however, there are deep

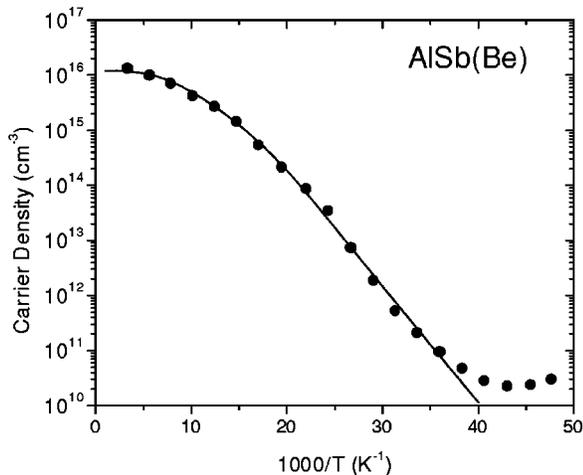


FIG. 4. Net carrier concentration as a function of temperature for a sample with 3- μm -thick AlSb(Be) on Si-GaAs. Solid line is calculated using $N_A = 1.3 \times 10^{16}/\text{cm}^3$, $E_A = 38$ meV, and $N_D = 1 \times 10^{15}/\text{cm}^3$.

donors, the holes from Be atoms would first have to compensate the donors before yielding p -type material.

To put an upper limit on the concentration of deep donors, we subtracted constant values of 10^{14} , 10^{15} , 10^{16} , and 10^{17} cm^{-3} from the $ce^{-E_a/kT}$ fit (solid curve) in Fig. 3. The results are shown as dotted lines. It is clear that donor concentrations of 10^{16} – 10^{17} cm^{-3} are not consistent with our data. The experimental points can, however, be fit reasonably well by background deep donors in the 10^{14} – 10^{15} cm^{-3} range. This is consistent with our fit to the variable-temperature data (Fig. 4) with $N_D = 1 \times 10^{15}/\text{cm}^3$. In addition, the good agreement between the GaAs(Be) and AlSb(Be) doping levels argues against a high deep-donor background in AlSb. Other groups have also estimated background donor concentrations in AlSb. Ideshita and Furukawa measured carrier concentrations in InAs/AlSb single quantum wells and inferred values of the donor concentration in AlSb of 1.5×10^{17} and $5 \times 10^{15}/\text{cm}^3$, depending upon the oxygen content of the source Sb.²⁰ Using similar test structures, Nguyen *et al.* found values of 2×10^{15} and $1.0 \times 10^{16}/\text{cm}^3$ during different MBE growth cycles.²¹

The samples represented in Fig. 3 were all grown in the same growth cycle. We grew several additional samples with $T_{\text{Be}} = 620$ °C in other growth cycles. The net carrier concen-

tration varied from 1 to $4 \times 10^{16}/\text{cm}^3$, consistent with a background donor concentration that is $>10^{16}/\text{cm}^3$ at times. In addition, the samples for this study were grown with the As cell at idle temperature (base=200 °C; cracking zone =400 °C) and the As valve closed during the entire ~ 4 h growths. In contrast, the InAs/AlSb quantum wells in Ref. 18 were grown with the As cell at growth temperature (base =370 °C; cracking zone=875 °C), and the As valve open during the InAs layer. Hence, it is quite reasonable to expect a higher concentration of As in the AlSb for the quantum well samples. One possible source of deep donors is As_{Al} .¹⁷ We also note that the apparent donor background level for AlSb(Si) increased by $\sim 10^{16}/\text{cm}^3$ when the As cracker zone was heated during growth (samples C and D in Fig. 1).

IV. SUMMARY

In summary, our results demonstrate that Be is a robust source for AlSb(Be) doping from 10^{15} cm^{-3} to at least 10^{19} cm^{-3} . Unlike some of the AlSb(Si) samples, none of the AlSb(Be) layers were “resistive.” Transport measurements of lightly Be-doped AlSb layers can be used as a means to estimate background impurities in AlSb films.²² Such measurements could be used as a routine characterization tool for antimonide MBE or metalorganic chemical vapor deposition systems, similar to GaAs(Si) epilayers for arsenide systems. Other materials such as GaSb and InSb would be less suitable because undoped GaSb epilayers are *p*-type,²³ with $(N_A - N_D) > 10^{16}/\text{cm}^3$, and InSb has a high intrinsic carrier concentration, $n_i \sim 2 \times 10^{16}/\text{cm}^3$ at 300 K.

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¹J. B. Boos, W. Kruppa, B. R. Bennett, D. Park, S. W. Kirchoefer, R. Bass, and H. B. Dietrich, *IEEE Trans. Electron Devices* **45**, 1869 (1998); J. B. Boos, M. J. Yang, B. R. Bennett, D. Park, W. Kruppa, C. H. Yang, and R. Bass, *Electron. Lett.* **34**, 1525 (1998).

²M. Johnson, B. R. Bennett, M. J. Yang, M. M. Miller, and B. V. Shanabrook, *Appl. Phys. Lett.* **71**, 974 (1997).

³D. H. Chow, H. L. Dunlap, W. Williamson, S. Enquist, B. K. Gilbert, S. Subramaniam, P. M. Lei, and G. H. Bernstein, *IEEE Electron Device Lett.* **17**, 69 (1996).

⁴J. R. Meyer *et al.*, *IEE Proc.-J: Optoelectron.* **145**, 275 (1998).

⁵e.g., F. Fuchs, J. Schmitz, H. Obloh, J. D. Ralston, and P. Koidl, *Appl. Phys. Lett.* **64**, 1665 (1994).

⁶e.g., E. R. Glaser, T. A. Kennedy, B. R. Bennett, and B. V. Shanabrook, *Phys. Rev. B* **59**, 2240 (1999).

⁷e.g., H.-J. Gossmann, G. P. Schwartz, B. A. Davidson, and G. J. Gualtieri, *J. Vac. Sci. Technol. B* **7**, 764 (1989); B. R. Bennett and B. V. Shanabrook, in *Heteroepitaxy: Thin Film Systems*, edited by W. K. Liu and M. B. Santos (World Scientific, Singapore, 1999), pp. 401–452.

⁸S. Subbanna, G. Tuttle, and H. Kroemer, *J. Electron. Mater.* **17**, 297 (1988).

⁹Y. Zhao, M. J. Jurkovic, and W. I. Wang, *Solid-State Electron.* **42**, 57 (1998).

¹⁰D. H. Chow, Y. H. Zhang, R. H. Miles, and H. L. Dunlap, *J. Cryst. Growth* **150**, 879 (1995).

¹¹MBE source materials were Al: IHT Corporation, 7N; Sb: Dowa Mining Co., 7N+.

¹²B. V. Shanabrook, J. R. Waterman, J. L. Davis, and R. J. Wagner, *Appl. Phys. Lett.* **61**, 2338 (1992).

¹³The 875 and 400 °C cracking zone temperatures are the values we typically use to obtain As_2 and As_4 , respectively. The valve, located between the As sublimator and the cracking zone, was closed during all AlSb growths. The heating of internal arsenic-coated surfaces in the MBE by a hot cracking zone, however, will cause a higher background As level in the system. In addition, the hot zone may dissociate background As_4 tetramers into As_2 dimers. Either mechanism could result in additional As incorporation into the growing AlSb films. Other impurities could also evaporate from the vicinity of the hot cracking zone and incorporate into the AlSb.

¹⁴C.-A. Chang, H. Takoaka, L. L. Chang, and L. Esaki, *Appl. Phys. Lett.* **40**, 983 (1982).

¹⁵P. D. Brewer, D. H. Chow, and R. H. Miles, *J. Vac. Sci. Technol. B* **14**, 2335 (1996); Y. Rouillard, B. Lambert, Y. Toudic, M. Baudet, and M. Gauneau, *J. Cryst. Growth* **156**, 30 (1995).

¹⁶D. J. Chadi, *Phys. Rev. B* **47**, 13478 (1993).

¹⁷J. Shen, J. D. Dow, S. Y. Ren, S. Tehrani, and H. Goronkin, *J. Appl. Phys.* **73**, 8313 (1993); J. Shen, H. Goronkin, J. D. Dow, and S. Y. Ren, *J. Appl. Phys.* **77**, 1576 (1995).

¹⁸F.-C. Wang, W. E. Zhang, C. H. Yang, M. J. Yang, and B. R. Bennett, *Appl. Phys. Lett.* **69**, 1417 (1996).

¹⁹X.-C. Cheng and T. C. McGill, *J. Vac. Sci. Technol. B* **16**, 2291 (1998).

²⁰S. Ideshita, A. Furukawa, Y. Mochizuki, and M. Mizuta, *Appl. Phys. Lett.* **60**, 2549 (1992); A. Furukawa and S. Ideshita, *J. Appl. Phys.* **75**, 5012 (1994).

²¹C. Nguyen, B. Brar, H. Kroemer, and J. English, *J. Vac. Sci. Technol. B* **10**, 898 (1992).

²²Relatively thick films of AlSb(Be) are required to measure low carrier densities. Using growth rates greater than $1 \mu\text{m/h}$ would reduce growth times. We grew an InAs/AlSb quantum well on GaAs (SI) with a $2\text{-}\mu\text{m}$ -undoped AlSb buffer layer. The AlSb was grown at $2.1 \mu\text{m/h}$. The 300 K (77 K) mobility was $25\,000 \text{ cm}^2/\text{V s}$ ($100\,000 \text{ cm}^2/\text{V s}$), comparable to quantum wells grown on conventional $1 \mu\text{m/h}$ AlSb buffer layers. This result suggests that AlSb(Be) films could also be grown at higher rates.

²³A. G. Milnes and A. Y. Polyakov, *Solid-State Electron.* **36**, 803 (1993).