Journal of ELECTRONIC MATERIALS, Vol. 33, No. 6, 2004

Fundamental Materials Studies of Undoped, In-Doped, and As-Doped $Hg_{1-x}Cd_xTe$

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Variable magnetic-field Hall and transient photoconductance-lifetime measurements were performed on a series of undoped, In-doped, and As-doped HgCdTe samples grown by molecular beam epitaxy (MBE). Use of quantitative mobility-spectrum analysis (QMSA) combined with multiple carrier-fitting (MCF) techniques indicates that the majority of samples contain an interfacial n-type layer that significantly influences the interpretation of the electrical measurements. This n-type layer completely masks the high-quality electrical properties of undoped or low n-type In-doped HgCdTe, as well as complicating the interpretation of activation in As-doped p-type HgCdTe. Introduction of an intentional n-type background, typically created through doping with In to "recover" high mobility, is actually shown to increase the "bulk" layer conductivity to a level comparable to the interface layer conductivity. Photoconductance-lifetime measurements suggest that In-doping may introduce Shockley-Read-Hall (SRH) recombination centers. Variable-field Hall analysis is shown to be essential for characterizing p-type material. Photoconductance-lifetime measurements suggest that trapping states may be introduced during the incorporation and activation of As. Two distinctly different types of temperature dependencies were observed for the lifetimes of As-doped samples.

Key words: HgCdTe, molecular beam epitaxy (MBE), doping, indium, arsenic, photoconductance lifetime, variable magnetic-field Hall, multiple carrier fitting (MCF), quantitative mobility-spectrum analysis (QMSA)

INTRODUCTION

While n-type doping of HgCdTe grown by molecular beam epitaxy (MBE) using indium is straightforward, extrinsic p-type doping remains difficult. Current technology relies on p-type doping typically achieved using As. However, incorporation mechanisms during MBE growth cause most of the As atoms to occupy either the Hg sublattice or interstitial sites and act as donors or neutral complexes, respectively. High-temperature anneals under Hg overpressure (or possibly lower temperature anneals without Hg) are then necessary to induce a site transfer to the Te sublattice. The process remains poorly understood, however, from both the technological and theoretical views. In addition, As_4 suffers from having a low sticking coefficient at the typical MBE-growth temperatures where the quality is highest (lowest dislocation density). This generally means that either the growth temperature must be lowered (possibly compromising material quality by increasing the dislocation density), or very high As fluxes must be used. An alternative is to use As_2 from a cracker source to increase the

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(Received October 15, 2003; accepted March 9, 2004)

sticking coefficient and possibly alter the incorporation mechanisms.[1]

Electrical characterization using Hall measurements is one of the cornerstone techniques for evaluating the quality and reproducibility of HgCdTe materials. It is particularly critical for studies of dopant activation such as that reported here. Mixed conduction effects can have a strong influence on magneto transport in HgCdTe, complicating interpretation of the Hall measurements. This is particularly true for epilayers, as conduction at substrate/epilayer interfaces and surfaces can dominate the transport. Variable magnetic-field Hall measurements can be used to determine, in principle, the influence of the various carriers and as such is a powerful characterization tool.[2] On the other hand, variable-field measurements add a significant degree of complexity to the process of sample characterization, which directly translates into increased time and characterization costs. Thus, each situation should be evaluated on a case-by-case basis to determine whether the added complexity is justified. For example, standard single-field Hall measurements are often adequate as a process control when many identical layers (or even structures) are grown and what is desired is a measure of reproducibility. However, to determine the interpretation of the process parameter measured by standard Hall data or to derive absolute values for mobility or carrier concentrations, variable-field measurements become necessary. The results of the present study indicate that variable-field Hall techniques are essential for evaluating multiple carrier transport in undoped, lightly In-doped, and As-doped HgCdTe. In addition, we report photoconductivity lifetime measurements that indicate high quality in the undoped and n-type material. The results obtained for As-doped samples are more ambiguous, with some measurements suggesting that heavy As doping may lead to trapping effects.

EXPERIMENTAL

A series of undoped, low In-doped, and As-doped HgCdTe layers with various compositions were grown at Rockwell Scientific Company (Thousand Oaks, CA) using MBE. The HgCdTe layer growth is detailed in a separate paper.[3] The undoped and In-doped samples have undergone standard n-type conversion (10 h at 245ºC) or an As-activation anneal at 430°C, followed by the n-type conversion anneal. Arsenic doping was accomplished with both conventional and cracker sources. Various anneals for various times at 370ºC and 430ºC resulted in different levels of activation in the As-doped layers. With an As-cracker cell, doping levels as high as mid-10^{20} cm^{-3} were obtained at low As-reservoir temperatures, although most of this As could not be activated. On the other hand, the activation efficiency could be as high as 100% for doping levels lower than $\sim 1 \times 10^{18}$ cm^{-3}, depending on the annealing conditions. Thus, the full sample set contains As-doped layers that are unactivated, partially activated, fully activated, and heavily compensated.

Resistivity and Hall measurements were made at West Virginia University (WVU, Morgantown, WV) as a function of temperature and magnetic field up to 4.5 T. The van der Pauw technique[4] was used on samples averaging 5 mm × 5 mm in size, with soldered In contacts, though, for compositions above $x = 0.43$, the use of an Hg-In eutectic was necessary to obtain ohmic contacts. Measurements were taken in a Janis (Wilmington, MA) SuperOptiMag System powered by a Cryomagnetics (Oak Ridge, TN) IPS-100 supply. At a given temperature, a total of 22 measurements were made with logarithmically spaced values of the magnetic field. All contact configurations and both current directions were measured using a Keithley 7001 switching unit (Cleveland, OH) with a 220 current source and 197A voltmeter. Quantitative mobility-spectrum analysis (QMSA) and multiple carrier fitting (MCF) were performed using standard techniques.[2,5]

For the temperature-dependent photoconductance-lifetime measurement, each sample was placed in a continuous-flow dewar in series with a variable direct-current source and a 50-Ω resistance. Optical excitation was performed with an Edmond Scientific 5-mW, 635-nm modulated laser diode driven by an Avtech (Ogdensburg, NY) 1002-C pulse generator. This excitation system had a fall time of about 40 ns. Changes in conductance were measured using a fast preamplifier to detect transient voltages across the 50-Ω resistance and recorded by a Tektronix TDS 684A digitizing oscilloscope. The background signal pickup from the pulse generator was reduced by first recording a trace with the laser blocked and then subtracting this from the measurements. An exponential least-squares fit was applied to the resulting transients to obtain photoconductance-decay lifetimes.

The Naval Research Laboratory (Washington, DC) provided assistance in implementing and interpreting the Hall and lifetime measurements. SRI International (Menlo Park, CA) provided interpretation to correlate detailed microscopic-material modeling studies with the experimental results.

VARIABLE MAGNETIC-FIELD HALL MEASUREMENTS

As a baseline for analyzing As-doped layers, we investigated whether the activation anneal itself significantly altered the fundamental properties of the HgCdTe layers. This part of the study turned out to be quite interesting in itself. Figure 1 shows MCF analysis results for two pieces of an undoped HgCdTe layer that went through either an n-type anneal or an activation-type anneal at 430ºC. The results are essentially identical to what was obtained using QMSA. The electrical properties of both samples were dominated by two electrons: one that is similar to the previously reported surface or interface electron[6] and the other with properties characteristic of the bulk of the sample. The results

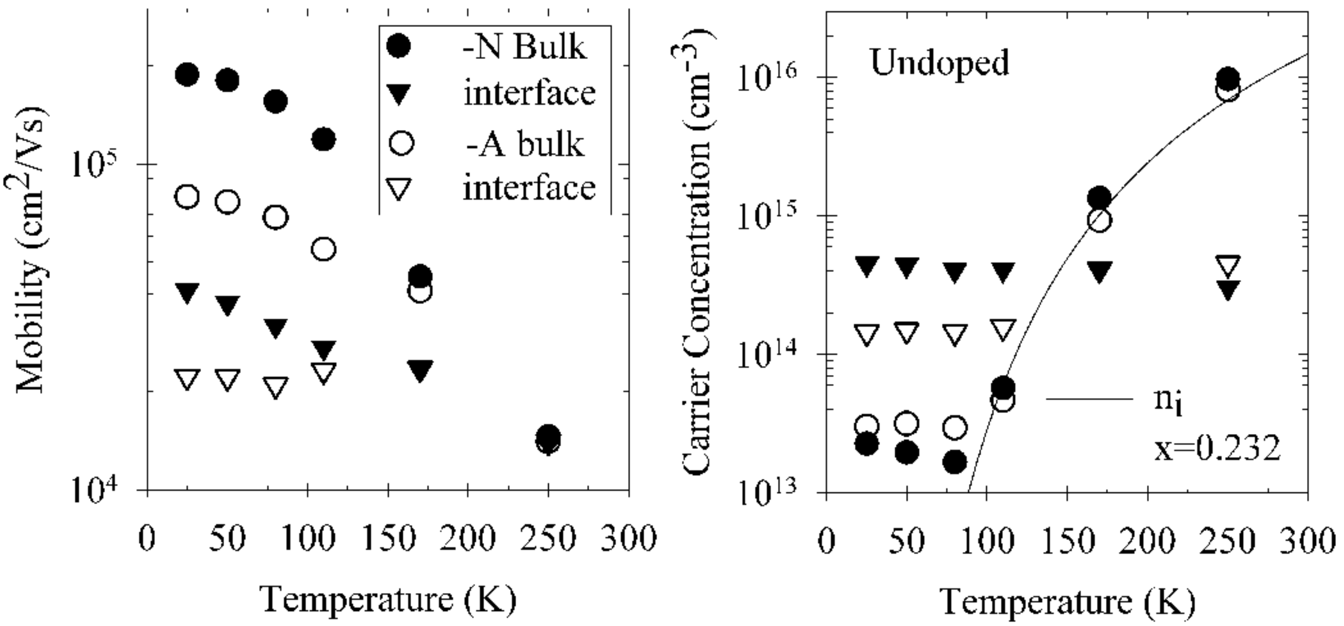

Fig. 1. Two-carrier MCF of the variable-field Hall data for two samples from the same undoped x = 0.232 wafer that were treated by either an "n-type" (N) or an "activation" (A) anneal at 430°C.

indicate high quality and very low doping. In particular, the n-type annealed sample had excellent mobility, and the measured carrier concentration closely tracked the predicted intrinsic dependence,[7] n_i, down to approximately 2–3 × 10^{13} cm^{-3}, followed by an essentially constant value below 80 K. The curve corresponding to the n_i calculation used the x value determined at Rockwell, with no other adjustable parameters. Mobility values for the "bulk" of the sample undergoing the 430ºC anneal were lower, suggesting that the anneal may have introduced defects that acted as scattering centers.

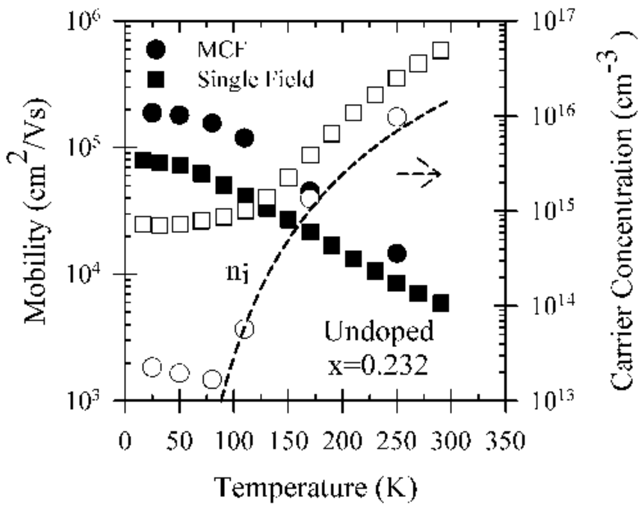

Fig. 2. Comparison of the results of single-carrier, single magnetic-field Hall measurements to those obtained from a multiple-carrier fit to the variable-field measurements. The closed symbols represent mobility, and the open symbols represent carrier concentration.

Figure 2 compares the results of single-field Hall measurements for the same sample with those obtained by MCF. This illustrates a very crucial point. The single-field result suggests a low mobility for this x value and a low-temperature carrier concentration over an order of magnitude larger than the MCF value. Many researchers have observed similar behavior in nominally undoped samples and attributed these properties to problems with the layers, such as mixed bulk conduction. The solution has been to add In as an n-type dopant, which effectively recovered the expected higher mobility but may have been unnecessary. Electrical measurements made on such a sample after a vacancy-removing anneal are shown in Fig. 3. While the single-field Hall results do indicate a higher mobility for this sample, additional insight is provided by the MCF analysis. In particular, two electrons are again present in the sample, with one again being tentatively assigned as belonging to an interfacial layer and the other to the HgCdTe layer itself. The significant difference is that now the conductivity of the epilayer dominates that of the interfacial layer, the reverse of the situation for the undoped sample. Note that Fig. 3 shows little difference between the mobilities of the undoped and In-doped layers when both are properly analyzed as multiple layer structures. Finally, the carrier concentration again closely tracks the predicted dependence of n_i on temperature using the x value determined from Rockwell, while the single-field results imply a concentration that is too large by about a factor of 3.

As an interesting side note, several of the low-doped n-type samples exhibited unexpected conductivity anisotropies in the van der Pauw voltages that were not at all consistent with the sample geometry. Some samples had anisotropy ratios as large as 50. We speculated that this was because of edge damage caused by cleaving and wondered if it could be the source of the "interfacial" electron. To test the

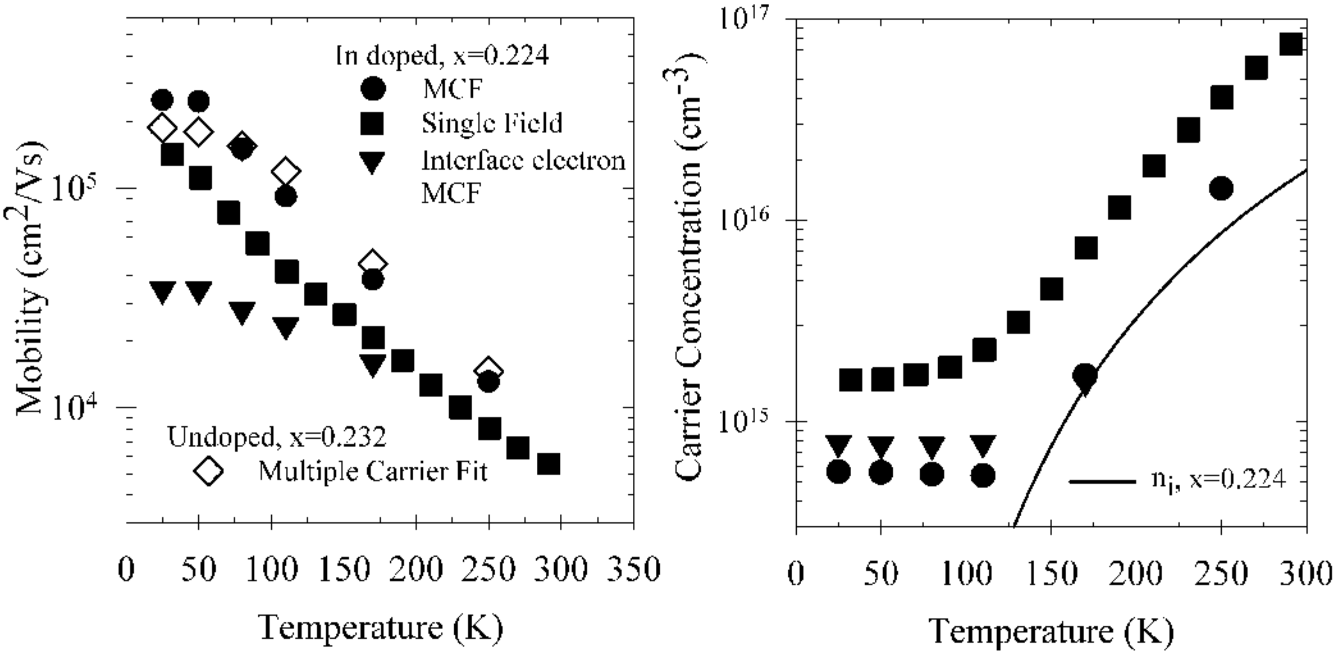

Fig. 3. Comparison of the results from single-carrier, single magnetic-field Hall measurements to those obtained from a multiple-carrier fit for an In-doped sample that was only annealed to remove Hg vacancies. The bulk mobility is similar to that in the equivalent undoped sample.

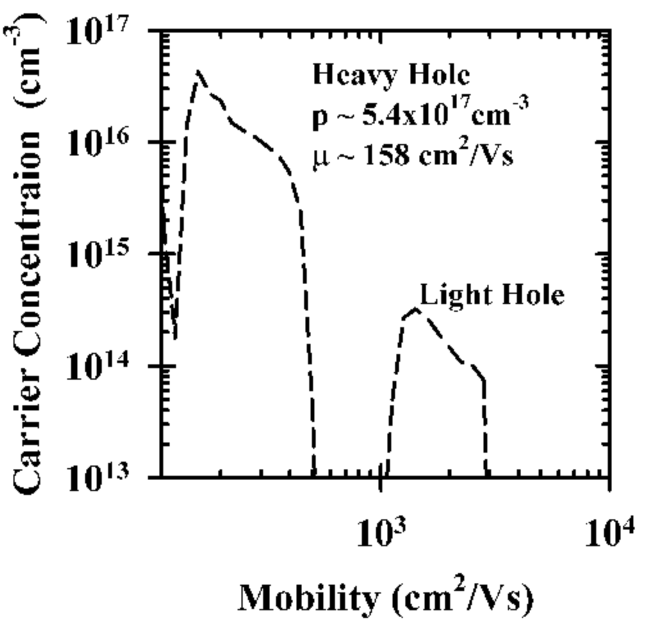

Fig. 4. The QMSA spectrum for a heavily p-doped sample (x = 0.31) measured at 75 K.

hypothesis, several samples exhibiting large conductivity anisotropy were etched into a cloverleaf pattern. This removed the conductivity anisotropy, but interestingly, did not significantly change the MCF Hall results. That is, two conduction electrons with the same values were measured for both sample configurations.

Figure 4 shows the QMSA spectrum obtained at 75 K from an As-doped HgCdTe (x = 0.31) sample annealed at 430°C. Similar results were obtained for both an unpassivated sample and a sample that was passivated with ZnS in an attempt to minimize surface effects. Both samples exhibited only light and heavy-hole conduction up to 250 K, where the intrinsic electron began to appear. The QMSA gave a total heavy-hole concentration (essentially equal to the total hole concentration) of about 5.4×10^{17} cm^{-3} with an average mobility of 158 cm^2/Vs, which is reasonably consistent with the single-field, single-carrier analysis result of $p \approx 5.2 \times 10^{17}$ cm^{-3} and $\mu_p \approx 170$ cm^2/Vs. For p-type samples dominated by a low-mobility carrier, we find that the best approach is to use QMSA (which needs no a priori assumptions) to determine the number and types of carriers. This information can then be used in the MCF, which requires a priori assumptions but tends to be more robust for analyzing samples dominated by lower mobility carriers as long as there is not a significant mobility spread.[6]

The MCF analysis allowed us to quantitatively determine both the light and heavy-hole mobilities and carrier concentrations in this heavily p-type sample. The temperature variations of these quantities are shown in Fig. 5. The MCF analysis indicates a slight increase in the heavy-hole concentration as compared to the single-field result, with a decrease in the 80-K mobility to 113 cm^2/Vs. Other studies have indicated similar results:[8–11] the light hole contributes at most between 1–5% of the total p-type conduction for layers with x ranging from 0.2 to 0.3, resulting in differences ranging between 20% and 60% for hole concentrations ranging from 10^{15} cm^{-3} to high 10^{17} cm^{-3}. If the light hole were the only consideration, the added complexity and cost of variable magnetic-field studies would probably not be justified as part of an As-activation study. While the light hole properties are important for understanding the fundamental physics of HgCdTe, as well as some

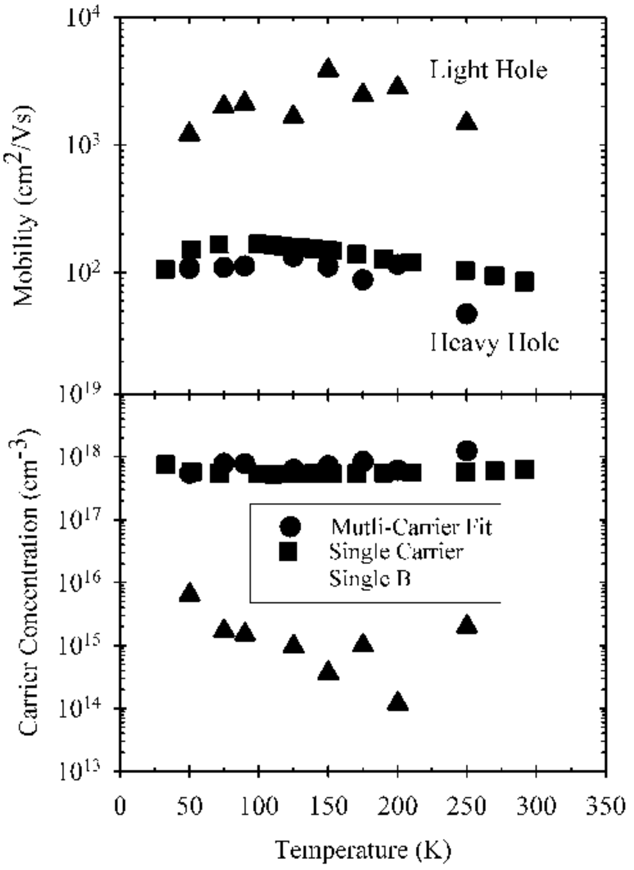

Fig. 5. Comparison of the MCF analysis to single-field Hall results for the heavily p-doped sample.

transport phenomena, the 40% apparent difference does not have a significant effect on the activation determined particularly if the contribution is consistent from sample to sample.

However, HgCdTe epilayers often exhibit n-type conductivity that is related to conduction at either a surface or an interface in the structure. This n-type conductivity can significantly affect the measurements in p-type layers, leading to anomalous results. This is illustrated by the results obtained from a second As-doped HgCdTe ($x = 0.31$) sample, also annealed at 430°C. While originally measured as p-type at Rockwell, with an 80-K hole concentration of $\sim 1 \times 10^{17}$ cm^{-3}, identical single-field measurements at WVU indicated that the sample was n-type with an electron concentration of 2×10^{16} cm^{-3}. Rockwell used front-surface, wire-bonded contacts, whereas soldered In contacts were used at WVU. The QMSA analysis, however, indicated that the conduction was due to the presence of both electrons and holes, with the higher mobility electrons dominating. Figure 6 shows the temperature variation of the results of variable magnetic-field Hall, as analyzed using the MCF technique assuming one electron and one hole based on the QMSA result. Clearly, the sample is strongly p-type over the entire temperature range investigated with a hole concentration of $\sim 1 \times 10^{17}$ cm^{-3} and an electron concentration of 2×10^{16} cm^{-3} at 80 K. Similar results were obtained for the electron concentration in the ZnS-passivated sample, although the hole concentration was affected at low temperatures. Subsequently, WVU was able to obtain p-type conduction on a companion piece by using lightly pressed front-surface In contacts. These results demonstrate that the front-surface condition does not significantly influence the properties of the electron species, which likely resides at the substrate/epilayer interface. The results also indicate a high degree of electrical isolation between the n- and p-type regions. Similar n-type layers were inferred previously to explain Hall data for low-concentration As-doped HgCdTe grown by MBE.[12]

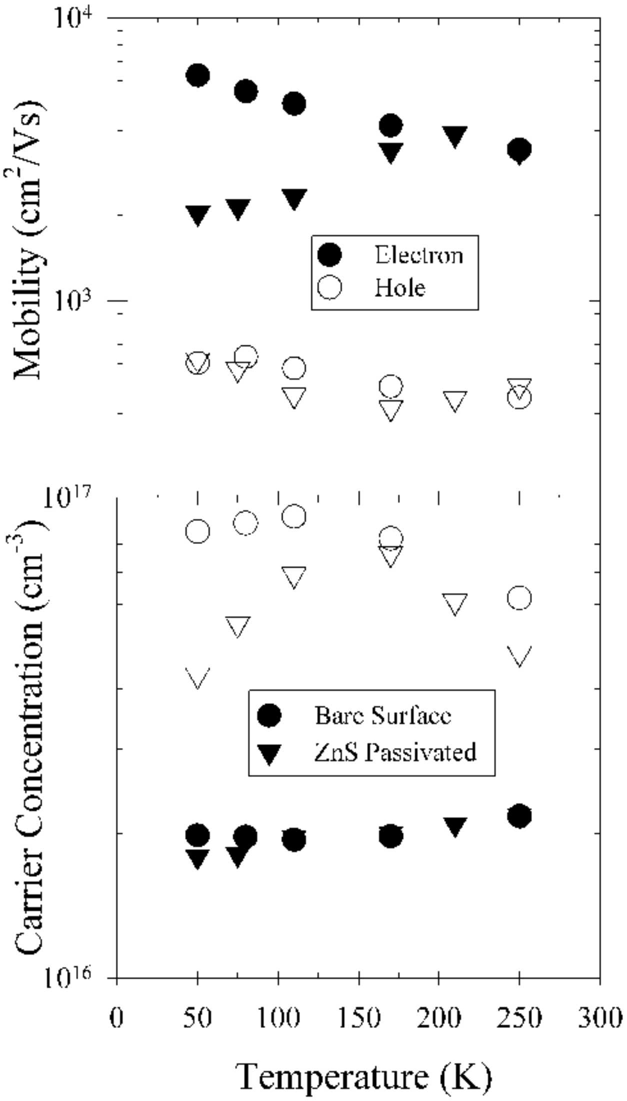

Fig. 6. The MCF analysis of this sample reveals a large p-type carrier concentration in addition to significant conduction from an n-type layer.

Tables I and II list 80-K MCF results for various n- and p-type samples. It can be seen that the interfacial layer significantly affects the electrical properties and sometimes has the larger conductivity. This underscores the necessity of employing variable-field

Table I. MCF Results at 80 K for n-Type Samples Receiving Only a 245°C n-Conversion Anneal

x	μ_B (cm^2/Vs)	μ_I (cm^2/Vs)	n_B (10^{14} cm^{-3})	n_I (10^{11} cm^{-2})	σ_B $(\Omega\ cm)^{-1}$	"σ_I" $(\Omega\ cm)^{-1}$
0.232	156,000	32,000	0.17	3.9	0.4	2.1
0.224	152,000	28,000	5.5	12	13	3.4
0.28	104,000	35,000	3.2	1.2	5.3	0.8
0.31	65,000	18,000	4.2	2.3	4.3	0.7
0.385	30,000	15,000	1.5	1.8	0.7	0.9
0.41	66,000	18,000	9.4	6.4	10	3.1

The x = 0.232 sample was undoped. All other samples listed were doped with In. Note the interfacial carrier concentration is given as a sheet value, but the interfacial "conductivity" is given as an equivalent conductivity for ease of comparison.

Table II. QMSA Results at 80 K for As-Doped Samples Receiving a 370°C Activation Anneal

x	μ_{hh} (cm^2/Vs)	μ_I (cm^2/Vs)	p_B (10^{16} cm^{-3})	n_I (10^{10} cm^{-2})	"σ_I" $(\Omega\ cm)^{-1}$	σ_{lh} $(\Omega\ cm)^{-1}$	σ_{hh} $(\Omega\ cm)^{-1}$
0.28	220	1,880	2.8	4.7	0.03	0.02	0.97
0.31	164	2,950	1.14	63	0.43	0.08	0.28
0.31	160	4,710	13	0.67	0.01	0.11	3.33

Note that interfacial conductivity can be more significant than light hole effects, especially for low-doped samples. Note the interfacial carrier concentration is given as a sheet value, but the interfacial "conductivity" is given as an equivalent conductivity for ease of comparison.

Hall analysis in As anneal and activation studies, as well as for studying the properties of lightly doped or undoped n-type material.

PHOTOCONDUCTANCE-LIFETIME MEASUREMENTS

The initial photoconductive-lifetime measurements were made on undoped and low In-doped HgCdTe. A comparison of the two for nominal x ~ 0.22 material is shown in Fig. 7. The very significant difference and, in particular, the very long lifetime in the undoped layer were not easily understood on the basis of the single-field Hall measurements. However, the results for the undoped layer can be explained in terms of Auger and Shockley-Read-Hall (SRH) recombination when viewed in light of the MCF shown in Fig. 1. The large lifetime difference clearly reflects the finding that the bulk electron concentration in the undoped sample is more than an order of magnitude lower than that in the doped sample. That the lifetime is as high as 20 μs following the higher temperature anneal confirms the quality of the layer growth and indicates that the As-activation anneal does not degrade the basic material quality. In fact, it may enhance the lifetime.

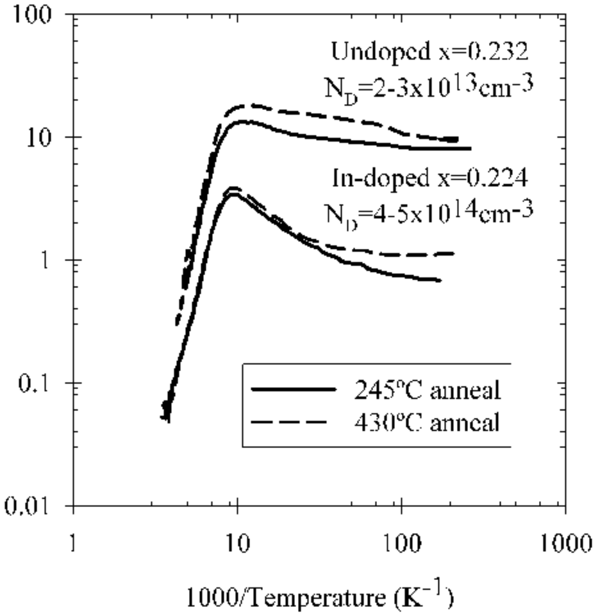

Fig. 7. Photoconductance-lifetime results for two n-type, x ~ 0.22 layers undergoing either a vacancy-removing anneal (245°C) or an As-activation-type annealing schedule (430°C).

The high-temperature dependence of lifetimes for both layers can be explained by the Auger process. As the temperature is increased, the intrinsic carrier density also increases and the Auger rate, which varies as the inverse square of the carrier density, thus decreases as seen in the experiment. The nearly temperature-independent behavior of the lifetimes at low temperatures can be due to either Auger and/or SRH scattering. However, if it is due to Auger, the lifetime can only be nearly flat or monotonically decrease in going to higher temperature. Thus, the observed peak near 100 K cannot be explained with Auger processes alone. We hypothesize that SRH centers and the movement of Fermi level (FL) with reference to those centers are responsible for the apparent increase in the lifetimes for the mid-temperature region. At low temperature, the SRH centers are assumed to coincide with the FL, which is near mid-gap. This is shown schematically in Fig. 8. The defect state density can be chosen to obtain the observed lifetime of 1 μs. As the temperature is increased, the SRH level is then assumed to follow the valance band. The new FL is obtained using full band-structure calculations. Because of the difference in electron and hole masses, the FL moves toward the conduction band and away from the SRH centers. Consequently, the SRH rate decreases.[13] We found that the predicted lifetime would increase by a factor of 3.5 based on this model when the temperature is varied from 25 K to 100 K, consistent with observed trends. We observed similar temperature-dependent lifetimes for In-doped HgCdTe with x ~ 0.3. A quantitatively more detailed analysis of these results is underway and will be published elsewhere.

Figure 7 strongly suggests that the In-doping process introduces SRH centers that were not present in the undoped HgCdTe. Moreover, the low-temperature photoconductance lifetime is always slightly longer following an As-activation anneal, whether or not the material is In-doped, indicating that such annealing may indeed reduce the concentration of SRH centers.

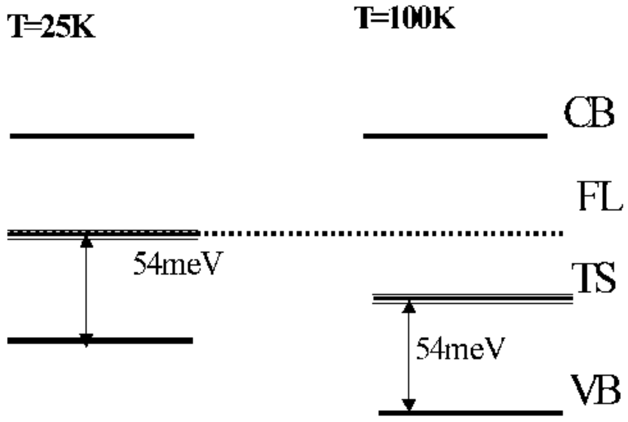

Fig. 8. If the dominant SRH centers track the valence (conduction) band, SRH recombination will exhibit a significant temperature variation, increasing at lower temperatures.

The lifetime analysis for the As-doped p-type material proved to be more complicated. In particular, two distinct types of behavior were observed. Figure 9a illustrates temperature-dependent photoconductance lifetimes measured for several As-doped, x ~ 0.3 HgCdTe samples. The single-field hole concentration for one of these samples is show in Fig. 9b. That the rapid decrease at high temperatures is due to Auger recombination is confirmed by the close correlation with an $1/n_i^2$ dependence. In a similar fashion, the rapid increase in the lifetime at the lowest temperatures appears to correlate well with the measured hole concentration, exhibiting carrier freeze out, scaling as $1/p^2$. This latter behavior strongly supports extrinsic Auger recombination as the dominant mechanism in that regime. This interpretation further implies that the flat portion of the lifetime curve at intermediate temperatures is consistent with Auger recombination continuing to dominate in the region where the measured carrier concentration is relatively constant. Recent calculations predict a region of constant lifetime for these temperatures and carrier concentrations.[14] On the other hand, dominance by the SRH process would be inconsistent with the sharp increase of the lifetime that is observed in the carrier freeze-out regime.

The true picture may be more complex. Many of the lifetimes reported for As-doped HgCdTe around 80 K appear too long, including several of the samples from this study. Figure 10 contains a compendium of 80-K photoconductance-lifetime results[15–21] for As-doped, x ~ 0.3 HgCdTe. Also

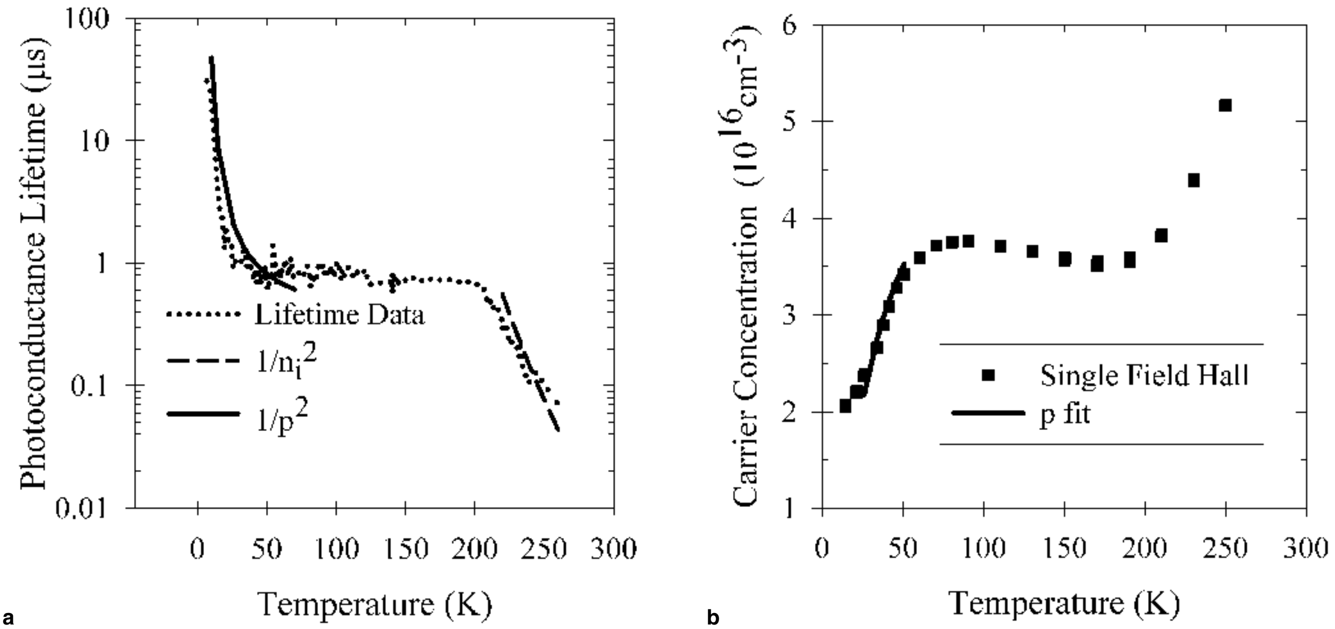

Fig. 9. Lifetime and single-field Hall results for a p-type sample (x = 0.31) that underwent a low-temperature (370°C) activation anneal.

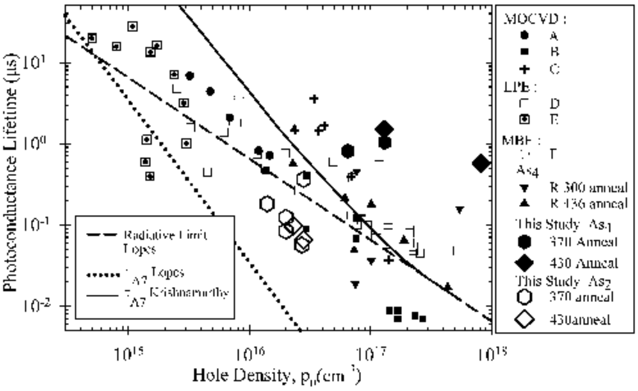

Fig. 10. Comparison of measured p-type photoconductance-decay lifetimes with calculations of theoretical-limiting mechanisms (A: Ref. 15; B: Ref. 16; C: Ref. 17; D: Ref. 18; E: Ref. 19; F: Ref. 20; and R: Ref. 21).

shown are the older calculations for radiative and Auger 7 recombination that are often compared to such data,[22] along with a newer treatment of Auger 7 recombination that is based on a full band-structure calculation.[14] Most of the measured values are in better agreement with the newer calculation, which serves as a reasonable upper bound. However, there remain a finite but significant number of samples that exhibit photoconductance lifetimes that are one or more orders of magnitude longer than predicted. Carrier trapping is one possible explanation for the observation of such long photoconductance lifetimes, particularly in the heaviest doped samples. Such a trapping effect has been reported for other p-type layers.[23]

Trapping is also strongly suggested by the photoconductance transients measured for several of the layers that exhibit temperature dependencies similar to those in Fig. 9. An example of such a transient is shown in Fig. 11. For certain temperatures, voltages, and pulse illumination levels, a “delayed” decay, which apparently indicates a long lifetime, can be seen. In addition, a slight rise in the photoconductance signal follows the initial rapid decay after the laser pulse is terminated. This rise is possibly due to emission by minority-carrier trapping centers. Similar behavior has been reported previously in HgCdTe and interpreted in terms of trapping effects on the recombination kinetics.[24]

The As dopants introduced during the MBE growth tend to occupy the Hg sublattice, to form As_{Hg}. An activation anneal shifts most of the As to the desired Te sublattice, As_{Te}, although the reaction also creates such byproducts as Te_I, Te_{Hg}, Te_{Hg}-V_{Hg} complexes, and As-related defects. While interactions with Hg during the activation and/or vacancy annihilation anneals should in principle eliminate many of these defects, the rates may be kinetically limited for heavy doping. All of these byproducts are candidate trap states. If the defect states have anion s-like symmetry, then conduction-band electrons (in p-type material, these are primarily photo-excited electrons) will readily transfer to the defect states. And because the electrons are now in states with s-like symmetry, the overlap integral with the valence band is small, and the Auger rate is greatly reduced. Thus, the recombination is limited primarily to radiative processes that are much slower rates than Auger, resulting in a long apparent lifetime. At lower temperatures, the valence holes freeze out, and the normal Auger rate can again dominate, while at high temperatures, carriers are thermally excited from both the valence band and trap states, and the intrinsic Auger lifetime begins to dominate.

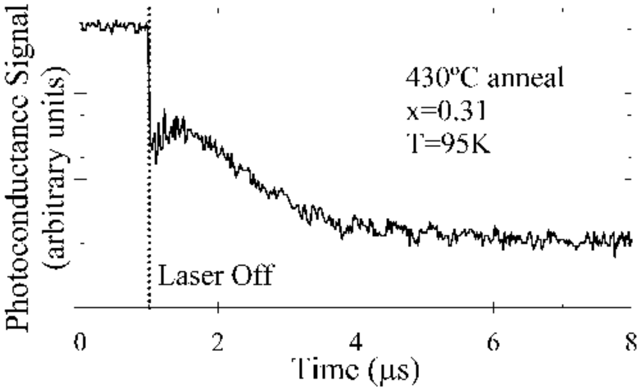

Fig. 11. The behavior of the photoconductance transient suggests that trapping may significantly influence recombination.

Calculations are underway to investigate which reaction byproducts exhibit the correct symmetry to serve as trap states. If the relevant state can be identified, then alternate annealing schedules may be possible to minimize that type of defect. We also plan to look at these samples with other techniques, such as steady-state photoconductivity and deep-level transient spectroscopy. It is hoped that this will lead to a conclusive determination of whether trapping phenomena actually cause the long lifetimes and assist in obtaining an estimate of the trap-level concentrations.

The second type of p-type photoconductance-lifetime variation with temperature is shown in Fig. 12. The 80-K lifetime is shorter than that observed for samples with the behavior shown in Fig. 11 and is more consistent with predicted Auger 7 and SRH-limited lifetimes. However, these samples exhibit a significantly different type of temperature variation. In general, the lifetime is fairly long at room temperature, followed by a continuous decrease of over a factor of 10 with decreasing temperature. This temperature variation is not predicted by calculations of the Auger 7 recombination and is not easily explained by the SRH mechanism either. Note also the sharp increase at the lowest temperatures that is apparently linked with carrier freeze out. Our preliminary finding is that this type of lifetime behavior only occurs for layers grown under As flux coming from the cracker source, with only one of seven such pieces exhibiting behavior similar to that in Fig. 9. All four of the samples grown with the standard thermal As source and measured at WVU exhibit behavior such as that found in Fig. 9.

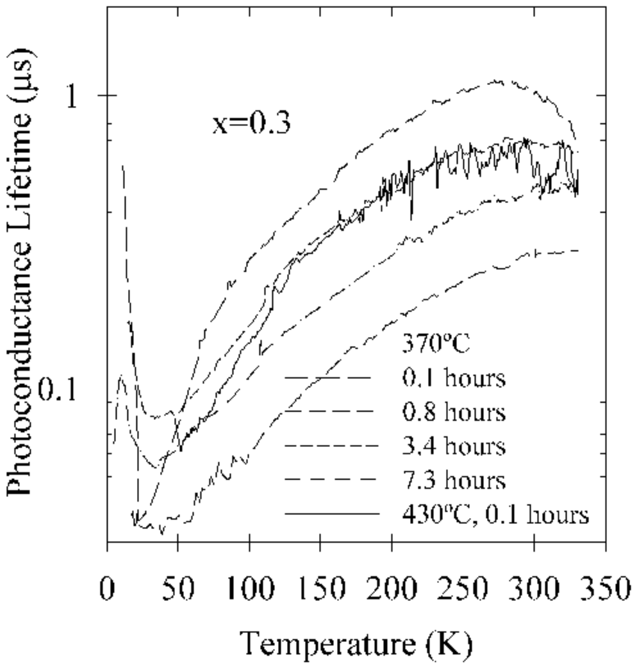

Fig. 12. Photoconductance-lifetime results for pieces of a p-type sample doped with an As_2 source and given various annealing treatments.

Clearly, more work is required before an unambiguous interpretation of the photoconductance lifetimes in As-doped HgCdTe grown by MBE will be possible. The significant fraction of samples with anomalously long, 80-K lifetime values, as shown in Fig. 10, suggests that similar issues may affect samples grown by a variety of techniques. In addition, the common practice of measuring (or reporting) only 80-K values for p-type material complicates the understanding of what is occurring in the material from various groups. We plan to carry out a detailed study on many additional As-doped samples and include steady-state photoconductivity and deep-level transient spectroscopy measurements to better understand the role of traps in these layers.

SUMMARY OF RESULTS

Variable magnetic-field Hall and transient photoconductance-lifetime measurements were performed on a series of undoped, In-doped, and As-doped HgCdTe. The use of QMSA combined with MCF techniques indicates that the majority of samples contain an n-type layer that significantly influences the interpretation of the electrical measurements. This n-type layer completely masks the high-quality electrical properties of the undoped or lightly n-type In-doped HgCdTe, as well as complicating the interpretation of activation in As-doped p-type HgCdTe. The n-type background that is typically imposed by In doping to “recover” high mobility is shown to have the effect of increasing the layer conductivity so that it is comparable to the interface layer conductivity. This may actually degrade the sample quality because photoconductance-lifetime measurements suggest that In doping can introduce SRH recombination centers. Variable-field Hall analysis is shown to be essential for characterizing p-type material. Photoconductance-lifetime measurements suggest that trapping states may be introduced during the incorporation and activation of As. Two distinctly different types of temperature-dependent lifetimes are observed.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the program and financial support of the Electro-Optics Center and the Air Force Material Lab, respectively (Contract No. N00014-99-2-0005).

REFERENCES

1. L.A. Almeida, *J. Electron. Mater.* 31, 660 (2002).
2. J.R. Meyer, C.A Hoffman, F.J. Bartoli, D.A. Arnold, S. Sivananthan, and J.P. Faurie, *Semicond. Sci. Technol.* 8, 805 (1993).
3. D. Edwall et al., *J. Electron. Mater.* 33, 752 (2004).
4. L.J. van der Pauw, *Philips Tech. Rev.* 20, 220 (1958).
5. I. Vurgaftman, J.R. Meyer, C.A. Hoffman, D. Redfern, J. Antoszewski, L. Faraone, and J.R. Lindemuth, *J. Appl. Phys.* 84, 4966 (1998).
6. J. Antoszewski, D.J. Seymour, L. Faraone, J.R. Meyer, and C.A Hoffman, *J. Electron. Mater.* 24, 1255 (1995).
7. J.R. Lowney, D.G. Seiler, C.L. Littler, and I.T. Yoon, *J. Appl. Phys.* 71, 1253 (1992).
8. Y. Gui, B. Li, G. Zheng, Y. Chang, S. Wang, L. He, and J. Chu, *J. Appl. Phys.* 84, 4327 (1998).
9. M.C. Gold and D.A. Nelson, *J. Vac. Sci. Technol. A* 4, 2040 (1986).
10. P.S. Wijewarnasuriya, M. Boukerche, and J.P. Faurie, *J. Appl. Phys.* 67, 859 (1990).
11. N.K. Talipov, V.N. Ovsyuk, V.G. Remesnik, and V.V. Schaschkin, *Mater. Sci. Eng.* B44, 278 (1997).
12. F. Aqariden, H.D. Shih, M.A. Kinch, and H.F. Schaake, *Appl. Phys. Lett.* 78, 3481 (2001).
13. S.M. Sze, *Physics of Semiconductor Devices* (New York: Wiley, 1981), p. 35.
14. S. Krishnamurthy and T.N. Casselman, *J. Electron. Mater.* 29, 828 (2000).
15. C.D. Maxey, C.L. Jones, N.E. Metcalfe, R.A. Catchpole, N.T. Gordon, A.M. White, and C.T. Elliot, *Proc. SPIE* 3122, 453 (1997).
16. P. Mitra, T.R. Schimert, F.C. Case, S.L. Barnes, M.B. Reine, R. Starr, M.H. Weiler, and M. Kestigian, *J. Electron. Mater.* 24, 1077 (1995).
17. M. Bevan, *Appl. Phys. Lett.* 67, 3650 (1995).
18. T. Tung, *J. Cryst. Growth* 86, 161 (1988).
19. D. Chandra, D.F. Weirauch, H.F. Schaake, M.A. Kinch, F. Aqariden, C.F. Wan, and H.D. Shih (Paper presented at the 2003 U.S. Workshop on the Physics and Chemistry of II-VI Materials, New Orleans, LA, 17–19 September 2003).
20. O.K. Wu, G.S. Kamath, W.A. Radford, P.R. Bratt, and E.A. Patten, *J. Vac. Sci. Technol. A* 8, 1034 (1990).
21. A.C. Chen, M. Zandian, D.D. Edwall, R.E. De Wames, P.S. Wijewarnasuriya, J.M. Arias, S. Sivananthan, M. Berding, and A. Sher, *J. Electron. Mater.* 27, 595 (1998).
22. V.C. Lopes, A.J. Syllaios, and M.C. Chen, *Semicond. Sci. Technol.* 8, 824 (1993).
23. Y. Nemirovsky, R. Fastow, M. Meyassed, and A. Unikovsky, *J. Vac. Sci. Technol. B* 9, 1829 (1991).
24. R. Pal, V. Gopal, P.K. Chaudhury, B.L. Sharma, P.K. Basu, O.P. Agnihotri, and V. Kumar, *J. Electron. Mater.* 30, 103 (2001).