P-Type Doping with Arsenic in (211)B HgCdTe Grown by MBE

P.S. WIJEWARNASURIYA, S.S. YOO, J.P. FAURIE, and S. SIVANANTHAN

Microphysics Laboratory, Department of Physics (M/C 273), University of Illinois at Chicago, 845 W. Taylor St., Room #2236, Chicago, IL 60680

Arsenic incorporation and doping in HgCdTe layers grown by molecular beam epitaxy (MBE) were examined in this paper. Arsenic incorporation into MBE-HgCdTe was carried out in two different ways: (1) ex-situ arsenic ion-implantation on indium-doped n-type HgCdTe layers, and (2) through a new approach called arsenic planar doping. We report on ex-situ arsenic diffusion on indium-doped MBE-HgCdTe layers at 450°C. In the investigated layers, arsenic redistribution occurs with a multi-component character. We obtained a diffusion coefficient of \( D_A = (1-3) \times 10^{-13} \) cm²/s at 450°C. Results of differential Hall and fabricated p-n junctions suggest that during high temperature annealing, arsenic preferentially substitutes into Te sublattices and acts as acceptor impurities. In the second case, arsenic has been successfully incorporated during the MBE growth as an acceptor in the planar doping approach. Without ex-situ annealing, as-grown layers show up to 50% activation of arsenic during the growth. These results are very promising for in-situ fabrication of infrared devices using HgCdTe material.

**Key words:** Arsenic, arsenic-planar doping, diffusion, HgCdTe, ion-implanted

---

**INTRODUCTION**

An understanding of the extrinsic and intrinsic doping process in molecular beam epitaxy (MBE)-HgCdTe is beneficial in obtaining high performance devices. Concerning the n-type case, indium has been extensively studied in MBE grown HgCdTe material.\(^1\)\(^-\)\(^4\) Indium doped layers show excellent electrical properties. Electron mobilities as high as \( 2 \times 10^6 \) cm²/V-s and minority carrier lifetimes in the order of 1 µsec at 80K for Cd composition \( x = 22\% \) are currently obtained. However, there are still many issues in the control of the p-type doping which remain to be solved.

P-type conductivity in MBE-HgCdTe can be obtained either with Hg vacancies or by electrically active impurities. Recently, there has been an increasing interest in p-type doping with external impurities due to the increase in minority carrier lifetimes.\(^5\) Among the external impurities, elements from group I and V are important. In principle, they can act as acceptors in HgCdTe if they are substituted for metallic (column II) sites and nonmetallic (column VI) sites, respectively. The MBE growth for HgCdTe occurs under Te-rich conditions\(^6\) and hence group I elements are favorable for p-type doping since they could easily be incorporated into metallic sites during the growth. Among the group I elements, incorporation of Li, Cu, Ag, and Au as p-type dopants in MBE-HgCdTe have been studied.\(^7\)-\(^8\) Unfortunately, the high diffusion coefficient of these elements in HgCdTe prevents their usefulness in FPA technology as p-type dopants.\(^7\)

In recent years, attention has been focused on arsenic as a p-type dopant due to its larger size and its low diffusion coefficient in HgCdTe material.\(^10\)-\(^12\) In MBE growth, the primary goal is to achieve the p-type doping at the growth temperature or after a low temperature anneal in order to preserve the integrity of the structure. If a high temperature anneal is required (>250°C), MBE will lose the advantages associated with its low temperature character, i.e., the possibility of creating a tailored profile in compo-

(Received October 29, 1996; revised March 21, 1996)
rated during the MBE process have been found to act primarily as donors in as-grown materials.\textsuperscript{10,13} This "intrinsic" difficulty in MBE explains why many approaches have been tried to achieve p-type doping in the MBE growth of HgCdTe using arsenic.\textsuperscript{14-21} However, most of these approaches demand a high temperature anneal (\textgreater 400°C) in order to activate arsenic.

In this paper, we will present results on arsenic incorporation into MBE (211)B HgCdTe layers grown at the Microphysics Laboratory (MPL) at the University of Illinois at Chicago (UIC). Arsenic incorporation into HgCdTe layers was carried out by: (1) \textit{ex-situ} arsenic ion-implantation on indium doped n-type HgCdTe layers, and (2) through a new approach called arsenic planar doping\textsuperscript{22,23} which appears to be very promising.

\section*{RESULTS AND DISCUSSION}

\subsection*{Experiment}

The HgCdTe layers were grown in an ISA Riber 2300 MBE machine. The detail of the growth procedure has been previously reported.\textsuperscript{4} The Cd composition and layer thickness were determined at room temperature by infrared transmission measurements. The transport characteristics (carrier concentration and mobility) of the layers were measured by the van der Pauw technique for temperatures ranging from 300 to 23K and with a magnetic field up to 1.0 Tesla.

The arsenic profiles in this study were performed at Charles Evans & Associates by secondary ion mass spectrometry (SIMS) measurements using dynamic Cs\textsuperscript+ ion bombardment with a net impact energy of 14.5 Kev. The primary beam was rastered over an area of (250 \textmu m\textsuperscript{2} in these analyses with the detected secondary ions extracted from the central 85 \textmu m diameter of the crater.

\subsection*{Arsenic Diffusion in Implanted n-Type HgCdTe}

Arsenic implantation on indium doped layers was done at IICO in California and was done at 300K using arsenic ions at 300 Kev energy with a dose of \(1 \times 10^{14} \text{ cm}^{-2}\). To diffuse implanted arsenic into the layers and to activate the diffused arsenic, annealing was done at 450°C in a closed quartz ampoule with mercury. In addition, a second anneal was done at 250°C under isothermal conditions to annihilate the created Hg vacancies during the first high temperature anneal. Figures 1 and 2 show SIMS profiles after annealing at 450°C. The respective indium doping levels as measured by Hall-effect are also shown in the figures. As observed in the figures, after annealing, the arsenic redistribution has a multicomponent behavior. Similar arsenic multicomponent profiles were observed in metalorganic chemical vapor deposition (MOCVD)-HgCdTe layers by Bubulac et al.\textsuperscript{25} The profile of the first component decreases rapidly with depth and it extends to \sim 0.2 \mu m from the surface. The arsenic concentration decreased from \(3 \times 10^{18} \text{ cm}^{-2}\) to \(4 \times 10^{17} \text{ cm}^{-2}\). This component will provide a shallow
arsenic ion-implanted source during the annealing process. The second component extends deeper into the material with a Gaussian-like distribution. As explained in Ref. 25, in this region Hg-interstitials which were generated as a result of knock-out of Hg atoms in the radiative damaged region are abundant. Also, arsenic atoms present in the radiative damaged region will provide a diffusion source during the annealing. We have calculated (dashed line) theoretically the arsenic redistribution by assuming a constant diffusion coefficient as described by Fick’s law. Also, Fig. 2 shows two arsenic SIMS profiles on two different spots on the sample #75. Excellent reproducibility of this component can be seen which demonstrate that the diffusion in this region does not depend on the defect/void density in the material. In this study, we have calculated a diffusion coefficient of $1.4 \times 10^{-13}$ cm$^2$/s at 450°C. This value is in good agreement with the value obtained in the literature at 450°C which is $(1.9-2.6) \times 10^{-13}$ cm$^2$/s at 450°C on MOVPE HgCdTe layers. Figure 3 shows the diffusion length of arsenic vs the square root of the duration of annealing at 450°C on these MBE-HgCdTe layers. Also, for comparison purposes, we have included data of Ref. 25. As can be seen, our obtained data are in good agreement with the data of Ref. 25 and also the simple Gaussian diffusion model fits very well with MBE-HgCdTe material.

The third diffusion component shown in Figs. 1 and 2 is a fast component. Arsenic is most probably diffused through metal sites in this region. Among the metal sites, Hg vacancies are dominant especially at 450°C and have the highest diffusion rate. Hence, the diffusion process will be affected by the dislocations (etch pit density [EPD], void density etc.) in the material. EPD in these two layers is under $=1 \times 10^4$ cm$^{-2}$. The depth $x_i$ in the material in this region is varying from sample to sample and even from different arsenic profiles as can be seen from Figs. 1 and 2.

Finally, to confirm the p-type character, we have fabricated some mesa p-on-n photo diodes on these arsenic ion-implanted layers. Our main intention in this part of the work was to demonstrate the arsenic p-type character and we have made no attempt to improve the diode characteristics. For an example, Fig. 4 shows I-V characteristics together with $R_{0A}$ at 80K for a layer which has a n-type doping level of $1.7 \times 10^{15}$ cm$^{-3}$, a low temperature mobility of $1 \times 10^4$ cm$^2$/V-s. and a Cd composition of 20.5%. We have obtained $R_{0A} = 1.7 \Omega$$\cdot$cm at 80K. These results confirm the p-type character of implanted and diffused arsenic on MBE-n-type HgCdTe layers.

**Arsenic Planar Doping**

In the planar doping technique, CdTe and Te effusion cell shutters are periodically closed and the arsenic effusion cell shutter is open during the MBE growth. The HgCdTe periodicity interval ranges from

![Graph showing diffusion length of arsenic vs square root of annealing time.](image)

**Fig. 3.** Diffusion length of arsenic vs square root of annealing time.

![Graph showing current-voltage characteristics.](image)

**Fig. 4.** Current-voltage characteristics of arsenic implanted on indium doped LWIR MBE-HgCdTe diode at 80K.

![Diagram showing cell shutters.](image)

**Fig. 5.** Schematic representation of planar doping of arsenic in MBE-HgCdTe.
30 to 200Å and for a few seconds the arsenic shutter cell is open while the Hg flux is still impinging on the surface. This is expected to enhance the Hg-As bond formation. Figure 5 shows schematic representation of this arsenic planar doping technology in the (211)B direction.

Figure 6 shows the measured Hall characteristics vs reciprocal temperatures of a selected as-grown layer (#124) with a cadmium composition of 31.7% (medium wave infrared [MWIR] region). The arsenic was deposited with a periodicity of 136Å while HgCdTe growth was interrupted. As can be seen from the figure, p-type characteristics are observed below 50K with a doping level of $2.5 \times 10^{17}$ cm$^{-3}$ and a low temperature mobility of 300 cm$^2$/V-s.

Similar doping levels have been obtained in the long wave infrared (LWIR) wavelength region. Figure 7 shows Hall characteristics of an as-grown arsenic planar doped layer with a Cd composition of 24.2%. This layer has a doping periodicity of 96Å. As can be seen, a p-type doping level of $6 \times 10^{16}$ cm$^{-3}$ has been achieved. Low temperature mobility is about 200 cm$^2$/V-s. In both cases for the MWIR and LWIR regions, the obtained doping level is clearly one order of magnitude higher than the intrinsic doping related to the Hg-vacancies during the MBE growth which implies that electrically active arsenic is incorporated during the growth process.

We have annealed as-grown layers under Hg saturated condition and measured Hall characteristics in order to gain a better understanding of the arsenic incorporation mechanism. Figure 8 shows Hall characteristics vs reciprocal temperature of layer #101 after n-type anneal. This layer has been annealed at high temperature in order to fully activate the arsenic. Annealing was performed in a closed quartz ampoule with saturated mercury. In addition to this anneal, a second anneal was done at 250°C under isothermal conditions to annihilate the created Hg-vacancies generated during the first anneal. As can be seen after isothermal annealing, the doping level increased from $6 \times 10^{16}$ cm$^{-3}$ to low $10^{17}$ cm$^{-3}$ level. This indicates that about 50% of arsenic was activated.
during the MBE growth assuming 100% electrical activity after the high temperature anneal. To confirm these results, we have also performed SIMS analysis of as-grown layers to measure the concentration of arsenic in MBE-grown layers and, therefore, to determine the percentage of active arsenic incorporated at the MBE growth temperature. Figure 9 shows the arsenic depth profile for as-grown layer #124. As evidenced from this graph, arsenic profiles are associated with peak structures and we believe that these are due to the periodic nature of arsenic distribution. High resolution SIMS measurement need to be done for further confirmation. Also, the respective doping concentration as obtained by Hall effect measurement is indicated in the Fig. 9. The arsenic concentration (by SIMS) of #124 is $5.0 \times 10^{17} \text{cm}^{-3}$ and the measured Hall concentration is $2.5 \times 10^{17} \text{cm}^{-3}$. Hence, the electrical activity of arsenic for layer #124 is also of 50% during the MBE growth of HgCdTe. These results attest that the incorporation of arsenic as an acceptor dopant during HgCdTe growth by MBE with an activation yield up to 50% has been achieved by using a planar doping approach which has never been used before for HgCdTe. These preliminary results represents a very important step toward advanced MBE-based HgCdTe technology.

**SUMMARY**

In this work, we report the results of arsenic incorporation in MBE-HgCdTe layers. Arsenic incorporation into MBE-HgCdTe layers was carried out in two different ways. In the first approach, arsenic diffusion on MBE-grown indium doped HgCdTe layers was observed at 450°C when diffused from an ion-implanted source. In the layers investigated, arsenic redistribution occurs by multicomponent mechanism. We have obtained a diffusion coefficient of $(1-3) \times 10^{-13} \text{cm}^2/\text{s}$ at 450°C. In the second approach (called the arsenic planar doping), arsenic was successfully incorporated during the MBE growth as acceptors. SIMS and annealing measurements confirm that arsenic is electrically incorporated into MBE-HgCdTe layers with an activation yield of up to 50% during the MBE growth. This work confirms that arsenic can be used as an effective acceptor dopant at MBE growth temperature of HgCdTe. These findings are very promising in the MBE-HgCdTe FPA technology.

**ACKNOWLEDGMENTS**

This work was funded by the Advanced Research Projects Agency and monitored by the U.S. Air Force Office for Scientific Research under contract # F49620-94-C-0080. Some of the layers were grown at EPIR and EMD under AFOSR-ARPA contract # F49620-91-C-0007.

**REFERENCES**


---