Ultra low background InGaAs Epi-layer on InP for PIN applications by production MBE

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Abstract

By optimizing the MBE growth condition for the InGaAs layer on InP substrate, ultra-low InGaAs background concentration has been achieved. Hall measurements at room temperature show background concentration level of less than 3e14 cm^{-3}, with mobility as high as 12,300 $cm^2/V\cdot s$. While, C-V measurements show background concentration has decreased to 1e14 cm^{-3} level with PIN photodetector epi structure. Commercial InGaAs PIN devices at 2 V reverse bias operation with an average 3 dB bandwidth of 4.6 GHz have been successfully fabricated from these MBE materials. For a 75 µm diameter device, room temperature dark current of 0.5 nA, and 1550 nm photo responsivity of 0.95 A/W were measured.

I. Introduction

For many of the InP-based optoelectronic applications, such as 1.3 and 1.5 µm InP PIN photodetectors, the background concentration of the intrinsic InGaAs needs to be as low as possible. Previously, reaching levels much below 1e15 cm^{-3} with mobility much above 7,000 $cm^2/V\cdot s$ at room temperature had been very difficult for MBE grown materials [1-4]. The higher intrinsic InGaAs background limits the operating window of a PIN photodetector. For example, a reduction of the detector's photo response could be traded to maintain low reverse bias voltage requirement. This can be achieved by reducing the thickness of the intrinsic InGaAs layer to ensure full depletion at lower reverse bias operating voltage. Conversely, lower reverse bias voltage requirement can be sacrificed to obtain higher detector photo response. The ability to achieve substantially lower InGaAs background level with MBE offers some unique opportunities such as the monolithic integration of advanced OEIC by combining a PIN photodetector epi structure with a well developed high performance InP-based HBT on a single epi growth. This is especially true for the integration with C-doped base InP HBT, where very high C doping of up to 1e20 cm^{-3} can be easily achieved with MBE while not yet available with MOCVD due to hydrogen passivation issue.

In this work, we have developed a much-improved InGaAs growth method yielding background doping levels within 1e14 cm^{-3} according to C-V measurements, and with room temperature Hall mobility as high as 12,300 $cm^2/V\cdot s$. Photoreflectance measurements also confirmed the improved InGaAs background doping level achieved with an optimized MBE growth condition. Commercial InGaAs PIN photodetectors for 2 V reverse bias voltage operation with an average 3 dB bandwidth of 4.6 GHz have been successfully fabricated from these low intrinsic background MBE materials, which were grown with multi-wafer MBE reactors. A typical 75 µm PIN device has room temperature photo responsivity of 0.95 A/W at 1550 nm and dark current of 0.5 nA at 2 V bias.

II. Epi material growth

InGaAs epi materials lattice-matched to InP with ultra low background doping have been developed for multi-wafer production MBE systems. The epi materials presented in this work were grown on 4" semi-insulating InP substrates using Riber6000 reactors. For 4" substrate, a Riber6000 is capable of growing up to 9 wafers at a time. The growth parameters such as substrate temperature profile, growth rate, and the V/III ratio were varied to find the best growth condition. Absorption Band-Edge Spectroscopy (ABES) was used to monitor critical substrate temperature profile, particularly at temperature below pyrometer range [5]. Optical-based Flux Monitor (OFM) was used to monitor the group III fluxes for precise control of InGaAs composition [6]. The epi structure for the InGaAs PIN Photodetector is shown in Fig. 1.

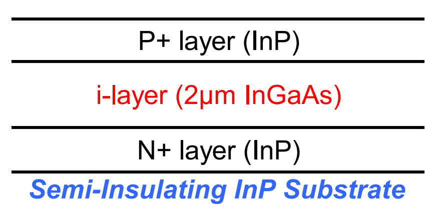

Fig. 1. PIN photodetector epi structure.

Typical indium composition for the InGaAs layers lattice-matched to InP substrate is confirmed by x-ray diffraction to be within 53 ± 0.6%. Typical thickness and doping uniformity for the epi materials across the growth platen are within ± 1%. Typical particle count for the PIN epi growth is below 30 particle/cm^2 across each of the wafers. The surface mapping was performed using 0.8 to 7.7 µm diameter scan range with a KLA Tencor Surfscan. To confirm reproducibility, the optimized growth condition was also successfully repeated several times with the same reactor as well as with other reactors.

III. Intrinsic InGaAs characterization

A. Hall measurements

According to literature [1-4], the background for MBE grown intrinsic InGaAs has been around low 10^{15} cm^{-3} for n-type, which is several times above the nominal low 1e14 cm^{-3} from MOCVD grown materials [7]. To establish the optimum growth condition for the low background intrinsic InGaAs materials, a Hall measurement setup was used to characterize both the carrier concentration and the mobility of the InGaAs Hall samples. The Hall test structure consisted of 2 µm of intrinsic InGaAs grown on InP. The background density was estimated from the following relation,

$$N_e = N_s / \left(w_0 - w_{dep}\right), \quad (1)$$

where N_e is the 3D background doping concentration of the intrinsic InGaAs, N_s is the measured Hall sheet density, w_0 is 2 µm thickness of the InGaAs epi layer, and w_{dep} is the surface depletion thickness. Because surface depletion was not directly measured, w_{dep} was estimated based on surface pinning potential of around mid gap at 0.5 x 0.732 eV for InGaAs. Table 1 summarizes the data from the Hall test samples.

Table 1. Example Hall data for 2 µm InGaAs from MBE.

Growth condition	Ns (cm-2)	Mobility (cm2/V·s)	Estimated Ne (cm-3)
Typical MBE	2.0E+11	5,440	1.2E+15
Optimized MBE	2.9E+10	12,300	2.2E+14

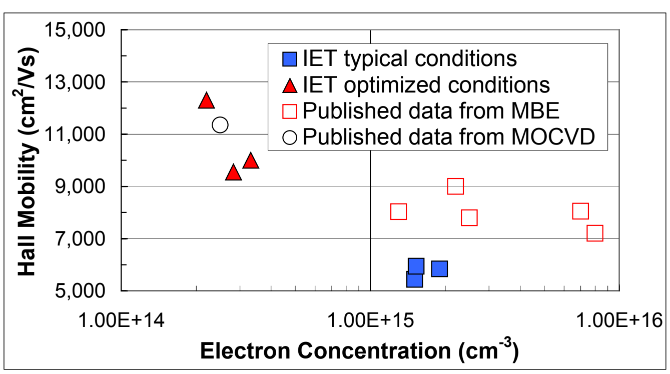

Fig. 2. Comparison of MBE InGaAs mobility vs. carrier concentration to published MBE [1-4] and MOCVD [7] data.

For our typical MBE growth condition, the InGaAs background was in the range of 1-2e15 cm^{-3} with the mobility of around 5,000 to 6,000 cm^2/V·s. With the optimized MBE InGaAs growth condition, Hall structures with background levels in the range of 2-3e14 cm^{-3} having mobility of up to 12,300 cm^2/V·s were observed. The mobility of the optimized MBE growth condition was comparable to MOCVD epi materials as shown in Fig. 2.

B. C-V measurements

To characterize the intrinsic InGaAs region of the PIN photodetectors, a C-V profiling technique was used to measure the background doping level of the epi materials. C-V data from typical and optimized MBE growth conditions are compared to data from MOCVD grown materials in Fig. 3a. From the C-V data, the intrinsic InGaAs region of the optimized MBE growth condition was almost fully depleted at 0 V bias. While the typical MBE growth condition required nearly 2 V of reverse bias to be fully depleted, and ~ 1.5 V for the MOCVD grown materials. For low voltage operation, it is critical for a PIN photodetector to be fully depleted at low reverse bias voltage.

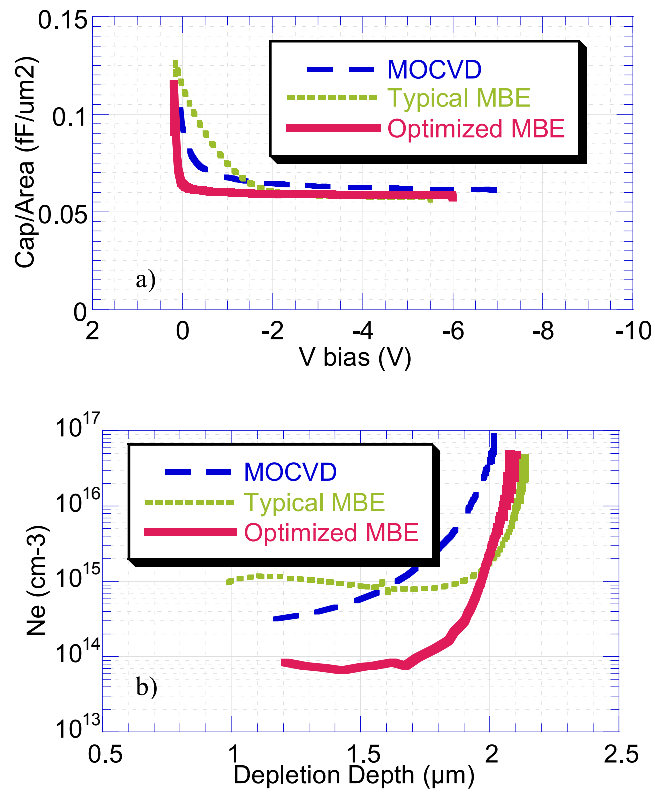

Fig. 3. Comparison of C-V data for InGaAs PIN structure from various growth methods. (a) C-V profile, (b) Doping profile.

From the C-V data, the corresponding doping profiles vs. depth from the two MBE growth conditions are compared to epi materials from MOCVD in Fig. 3b. The background doping level from the optimized MBE growth condition was below 1e14 cm^{-3}, which is several times lower than the MOCVD grown materials (2-5e14 cm^{-3}) and about an order of magnitude improvement over the typical MBE growth condition (1-2e15 cm^{-3}).

C. Photoreflectance measurements

Photoreflectance (PR) measurements at 300K were also performed on the full PIN photodetector structure to confirm the improved background doping level with the optimized MBE growth condition. The PR data corroborated the much-reduced background doping level observed by the C-V measurement for the optimized MBE growth condition. The PR spectra are shown in Fig. 4a.

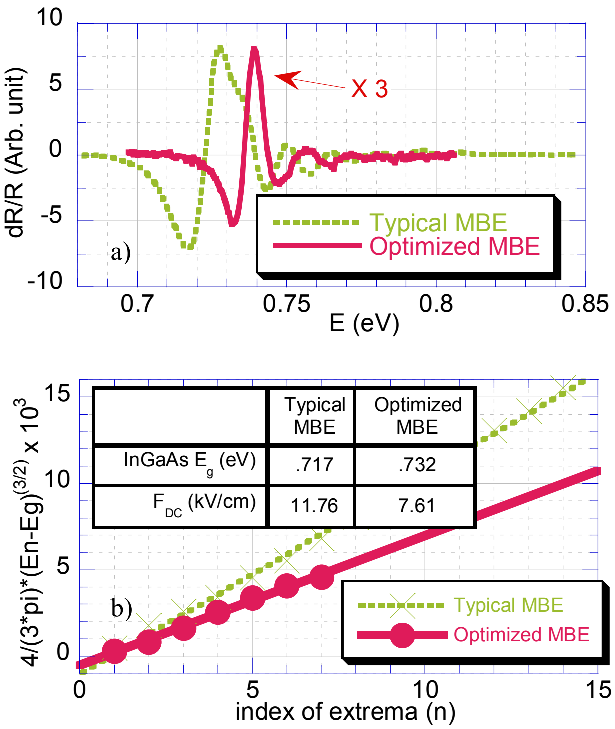

Fig. 4. Photoreflectance data from InGaAs PIN grown by MBE. (a) Photorefectance spectra, (b) Extrema from Franz-Keldysh Oscillation.

The electric field across the intrinsic InGaAs region was obtained from the observed Franz-Keldysh Oscillation (FKO) extrema given by [8-9]

$$n = \frac{4}{3\pi}\left[\left(E_n - E_g\right)/\hbar\Theta\right]^{3/2} + \varphi, \qquad (2)$$

where n is the index of the n^{th} extrema, φ is an arbitrary phase factor, E_n is the photon energy of the n^{th} oscillation, and E_g is the band gap energy of the intrinsic InGaAs region. The electro-optic parameter $\hbar\Theta$ is defined by

$$(\hbar\Theta)^3 = (e\hbar F_{DC})/2\mu_{\parallel}, \qquad (3)$$

where F_{DC} is the electric field and $\mu_{\parallel}$ is the reduced effective mass in the direction of F_{DC}. From the fits to the extrema vs. index n in Fig. 4b, the electric fields were 7.61 kV/cm for the optimized MBE growth condition, and 11.76 kV/cm for the typical MBE condition. From rough estimate, the background carrier is related to the electric field according to the following relation,

$$N_e = K \cdot F_{DC}^2, \qquad (4)$$

where K is the proportionality constant [10]. From the FKO of the optimized MBE growth condition, the F_{DC} corresponds to approximately 1.4e14 cm^{-3} of background concentration. While the typical MBE sample showed higher background of 3.2e14 cm^{-3} according to its FKO. Although the PR background concentration value for the typical MBE condition is a factor of 3 lower than the C-V measurement, the PR data does confirm the trend of reduced background with the optimized growth condition.

IV. PIN photodetector device results

PIN photodetectors for 2.5 Gbit/s applications operating at 2 V reverse bias with improved 3dB bandwidth were successfully fabricated from the optimized MBE epi materials. These devices were fabricated by Vitesse's 4" InP fabrication line. Fig. 5 is a picture of a commercial photodetector die with 75 µm diameter detection area. The dark current vs. the reverse bias voltage for a 75 µm device is shown in Fig. 6. At 2 V reverse bias, the measured dark currents were approximately 0.5 nA, well within the 1 nA requirement. The dark current remained below 1 nA nearly up to 20 V reverse bias. From 0 °C to 120 °C temperature range, the average photo responses at 1550 nm vs. bias voltage, as shown in Fig. 7, were fairly flat. The average photo responsivity at 2 V and 40 °C measurement condition was 9.5 A/W.

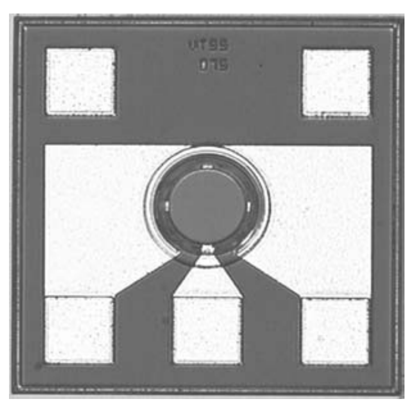

Fig. 5. Picture of 75 µm diameter PIN photodetector.

The box plot of the 3dB bandwidth vs. bias voltage for the 75 µm dies across a processed 4" InP epi wafer is shown in Fig. 8. The PIN epi wafer came from one of the MBE growth runs with the optimized condition. The measurements were taken at 40 °C and 1550 nm. At the 2 V reverse bias, the average 3dB bandwidth was approximately 4.6 GHz.

Histograms of the 3 dB bandwidth across each wafer from the previous epi materials and the newly optimized MBE growth condition are compared in Fig. 9. From the histograms, the averaged 3 dB bandwidth of the PIN device from the new materials increased by more than 40 %.

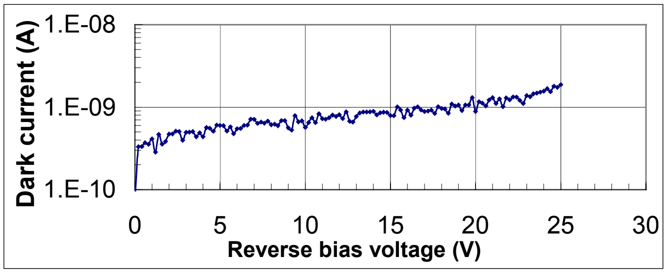

Fig 6. Dark current for 75um photodetector.

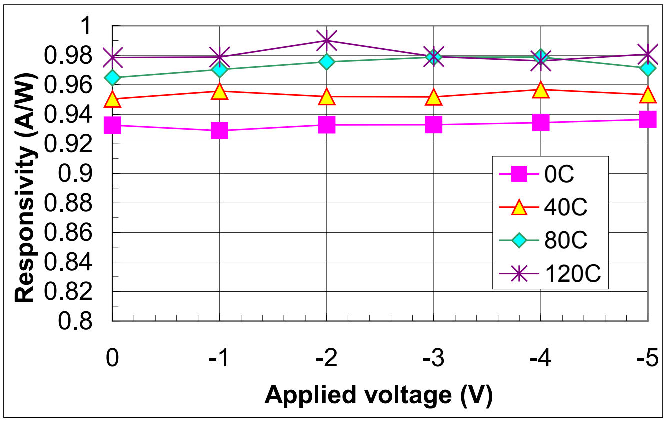

Fig 7. 75um PIN average responsivity @ 1550 nm.

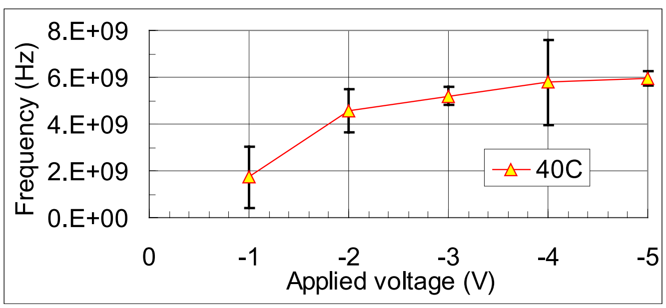

Fig. 8. 75um diameter PIN 3dB bandwidth @ 1550nm.

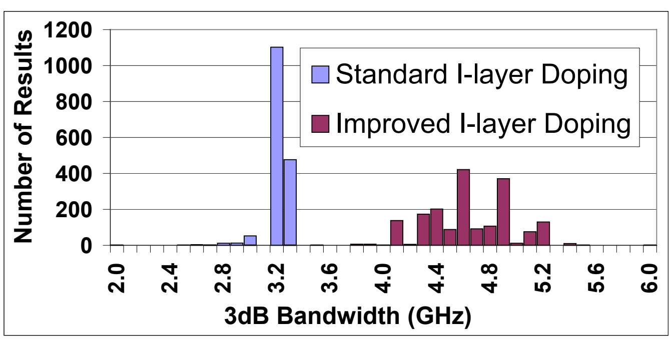

Fig. 9. Histogram of PIN 3dB bandwidth measured at 2 V reverse bias for all 75 μm detectors across 4" Wafer.

V. Conclusion

We have demonstrated the ability to grow intrinsic InGaAs epi materials with very low background doping concentration using multi-wafer production MBE. Hall measurements of 2 μm intrinsic InGaAs samples showed low background doping concentration in the low 1e14 cm^{-3} and high mobility of over 12,000 cm^2/V.s. From C-V, the PIN photodetector from the optimized MBE growth condition was measured to be below 1e14 cm^{-3}. The PR data also qualitatively confirmed the improvement of the background level with the optimized condition as observed by C-V. To our knowledge, this is the lowest intrinsic InGaAs background and highest mobility reported for MBE materials. High performance InGaAs PIN photodetectors reaching an average 3 dB bandwidth of 4.6 GHz at 2 V bias across 4" InP substrates have been fabricated from the optimized MBE grown materials. A 75 um device at 2 V reverse bias has dark current 0.5 nA, and photo responsivity of 0.95 A/W at 1550 nm.

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[10] Private communication with Prof. Fred H. Pollak, Physics Dept., Brooklyn College of CUNY, 2001-2002. *K* was empirically determined from a series of PR measurements cross-calibrated with HBT samples of various InGaAs collector doping level.