# Efficient Single-Heterojunction $Al_{0.27}Ga_{0.73}As/GaAs$ p-i-n Photodiodes with 22-GHz Bandwidths

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***Abstract*—We report on the design, fabrication, testing, and modeling of single-heterojunction $Al_{0.27}Ga_{0.73}As/GaAs$ p-i-n photodiodes for**

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**use as components in optical receivers. The photodiodes are grown by molecular beam epitaxy and fabricated as 1100-μm² mesa structures. At 5-V reverse bias and 850 nm, we typically measure 100 fF of capacitance, 90 pA of leakage current, 73% external quantum efficiency, <2% reflectivity, and 22-GHz bandwidths.**

## I. Introduction

GaAs has been recognized for at least 30 years as an excellent candidate for near-infrared photodiodes [1]. Although 3-dB bandwidths $f_{3dB}$ greater than 110 GHz have been achieved with Schottky barriers deposited on GaAs [2]–[5], considerable research continues on p-i-n photodiodes fabricated in GaAs. Results for some previously reported homojunction (HJ), single-heterojunction (SHJ), and double-heterojunction (DHJ) AlGaAs/GaAs p-i-n's are included in Table I.

The purpose of this brief is to demonstrate that simple AlGaAs/GaAs p-i-n photodiodes can easily satisfy the exacting specifications on leakage current, reliability, efficiency, reflectivity, and bandwidth required in high-performance optical receivers. In particular, we report on the growth, fabrication, testing, and modeling on SHJ $Al_{0.27}Ga_{0.73}As/GaAs$ p-i-n photodiodes with $f_{3dB} \sim 22$ GHz and external quantum efficiency $\eta = 73\%$.

## II. Experimental Approach

Our p-i-n photodiode is illustrated schematically in Fig. 1. The combination of a GaAs intrinsic layer, or i layer, and an $Al_{0.27}Ga_{0.73}As$ : Be window layer allows for wavelength coverage between 700 and 870 nm. We use a mesa structure with an active area of $\sim 1100\ \mu m^2$. The thickness of the GaAs i layer (see Fig. 1) is chosen to be 2 μm based on design rules [15] that should successfully balance capacitance, quantum efficiency, and photocarrier transit time. With a fully depleted 2-μm i layer, we calculate ~68 fF of capacitance and ~85% quantum efficiency at 850 nm.

The epitaxial layers are grown by molecular beam epitaxy on $n^+$ GaAs substrates in the following order: a 0.05-μm GaAs : Si buffer layer (n-type, $\sim 2 \times 10^{18}\ cm^{-3}$), a 2.0-μm GaAs i layer (undoped p-type, $< 10^{15}\ cm^{-3}$) and a 1-μm $Al_{0.27}Ga_{0.73}As$ : Be window layer (p-type, $2 \times 10^{18}\ cm^{-3}$). As shown in Fig. 1, photodiodes are fabricated by etching mesa structures and passivating the sidewalls with polyimide [16]. Using vias in the polyimide, bond pads are plated up from ring-shaped Ti/Pt/Au top metallization. The photodiodes include a single-layer silicon nitride antireflection coating. The silicon nitride coating is specified as 115 ± 5 nm thick with a refractive index at 850 nm of 1.85 ± 0.02.

All dc and high-frequency measurements are reported at 5-V reverse bias. Reflected optical power is measured with a swept modulation frequency technique that has been described previously [17]. Bandwidths are measured by illuminating packaged photodetectors with 1-ps pulses from an 80-MHz mode-locked 850-nm dye laser. The resultant photocurrent is viewed on a Hewlett-Packard spectrum analyzer.

## III. Results

For a sample of 239 photodiodes, the average leakage current is 86 ± 46 pA, corresponding to a mean leakage current density of $8 \times 10^{-6}\ A/cm^2$. Since the stability of this leakage current is critical for optical receivers, our photodiodes have been subjected to high-temperature operating life reliability tests at 175°C and 5-V reverse bias. In a sample of 40 photodiodes, we observed no failures (defined as a doubling of the leakage current) after 1000 h.

At 1 MHz, the photodiodes have a typical measured capacitance of 98 ± 6 fF, higher than the calculated value by ~30 fF. The bond pad shown in Fig. 1 accounts for 15–30 fF of this extra capacitance, depending on the exact polyimide thickness. This bond-pad capacitance could be reduced by using one of the semi-insulating (SI) designs referenced in Table I.

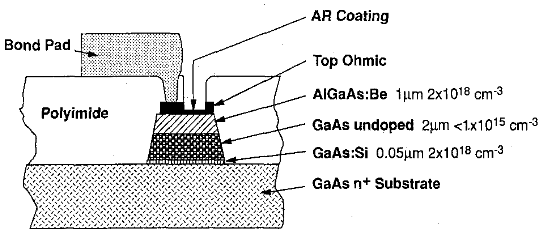


Fig. 1. Schematic diagram of the single-heterojunction $Al_{0.27}Ga_{0.73}As/GaAs$ p-i-n photodiode.

TABLE I
Results for AlGaAs/GaAs p-i-n's Reported in the Literature

| GaAs Substrate | Design | $f_{3dB}$ (GHz) | External $\eta$ (%) | λ (nm) | Reference |
|---|---|---|---|---|---|
| SI | HJ | * | 15 | 750 | [6] |
| Conducting | DHJ | * | 27 | 820 | [7] |
| Conducting | SHJ | 1.2 | 70 | 840 | [8] |
| SI | SHJ | 2.5 | 65 | 840 | [9] |
| Conducting | SHJ | 7 | 34 | 850 | [10] |
| SI | SHJ | 15 | 50 | — | [11]–[13] |
| SI | DHJ | * | 61 | 820 | [14] |
| Conducting | SHJ | 22 | 73 | 850 | this work |

The "*" indicates pulse response testing. SI means semi-insulating.

At 850 nm, the photodiodes have a typical measured external quantum efficiency $\eta = 73\%$ and power reflectivity <2%. Although the measured efficiency is slightly less than the expected value of ~85%, it exceeds other designs shown in Table I. Since our photodiodes simultaneously exhibit low leakage current (<90 pA) and high quantum efficiency ($\eta = 73\%$), they can be used as components in optical receivers that require excellent sensitivity and dynamic range. A bandwidth measurement of the relative optical response as a function of frequency is shown in Fig. 2. The data contain ±0.5 dB of random noise and there is evidence for package resonances at 4–5-GHz intervals. Nevertheless, we are clearly able to establish a value for $f_{3dB}$ of approximately 22 GHz.

## IV. Discussion

The optical response data in Fig. 2 can be modeled by using the p-i-n circuit model [18] shown in Fig. 3. The diode is represented by a junction capacitance $C_J = 98$ fF, a depletion region resistance $R_D = 100\ M\Omega$, and series resistance $R_S$. The diode package is represented by a package capacitance $C_P = 25$ fF and a package inductance $L_S = 0.1$ nH. We assume a load resistance $R_L = 50\ \Omega$. As shown in the inset of Fig. 3, the transit time of the photodiode is represented by a triangular current pulse with a 20-ps duration. Following procedures reported by Wang [18] and Parker [13], the response of the circuit to the current pulse is calculated by SPICE computer simulation. The results are included in Fig. 2 for a range of series resistance values: $0.5 \le R_S \le 25\ \Omega$. A series resistance $R_S = 10\ \Omega$ provides good agreement between the model and measured data.

We conclude that our photodiode bandwidth is limited by both the photocarrier transit time and the series resistance $R_S$. In addition, our analysis neglects that a fraction of the photocarriers are

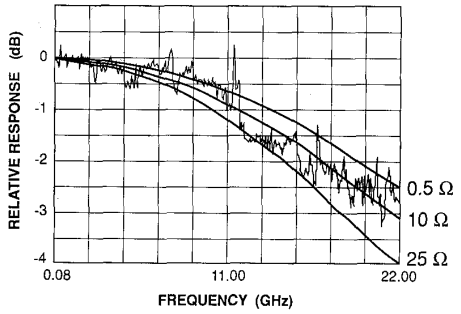


Fig. 2. Spectrum analyzer measurement of photodiode bandwidth. High-frequency circuit simulations of the photodiode are shown as solid lines for: $R_S = 0.5$, 10, and 25 Ω.

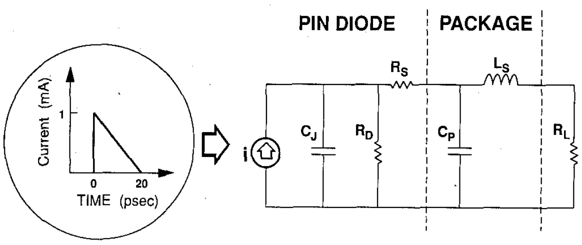


Fig. 3. Photodiode circuit model used for high-frequency circuit simulations. The inset shows a triangular current pulse of 20-ps duration.

generated in the bottom $n^+$ GaAs layer (see Fig. 1). Apparently, the diffusion length of these photocarriers is sufficiently short to support our measured bandwidth of ~22 GHz. For ultimate bandwidth performance, however, one of the DHJ designs referenced in Table I should be employed.

## V. Summary

In summary, we have manufactured SHJ $Al_{0.27}Ga_{0.73}As/GaAs$ p-i-n photodiodes. The photodiodes were grown by MBE and fabricated as mesa structures. At 5-V reverse bias and 850 nm, we typically measure 100 fF of capacitance, 90 pA of leakage current, 73% external quantum efficiency, <2% reflectivity, and 22-GHz bandwidths. A transit time of ~20 ps and a series resistance of 10 Ω give a reasonable simulation of the bandwidth data. These photodiodes are now being used in commercial optical receivers.


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