Efficient Single-Heterojunction Al$_{0.27}$Ga$_{0.73}$As/GaAs p-i-n Photodiodes with 22-GHz Bandwidths


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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I. Introduction

GaAs has been recognized for at least 30 years as an excellent candidate for near-infrared photodiodes [1]. Although 3-dB bandwidths \( f_{\text{3dB}} \) 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 \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs} \) p-i-n photodiodes with \( f_{\text{3dB}} \sim 22 \text{ GHz} \) and external quantum efficiency \( \eta \approx 73\% \).

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 \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \):Be window layer allows for wavelength coverage between 700 and 870 nm. We use a mesa structure with an active area of \( \approx 1100 \mu\text{m}^2 \). The thickness of the GaAs i layer (see Fig. 1) is chosen to be 2 \( \mu\text{m} \) based on design rules [15] that should successfully balance capacitance, quantum efficiency, and photocarrier transit time. With a fully depleted 2-\( \mu\text{m} \) layer, we calculate \( \sim 68 \text{ fF of capacitance and } \sim 85\% \text{ quantum efficiency at 850 nm.} \)

The epitaxial layers are grown by molecular beam epitaxy on n'-GaAs substrates in the following order: a 0.05-\( \mu\text{m} \) GaAs:Si buffer layer (n-type, \( \sim 2 \times 10^{18} \text{ cm}^{-3} \)), a 2.0-\( \mu\text{m} \) GaAs i layer (undoped p-type, \( <10^5 \text{ cm}^{-3} \)) and a 1-\( \mu\text{m} \) \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \):Be window layer (p-type, \( 2 \times 10^{18} \text{ cm}^{-3} \)). 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/Ag/Au 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 a 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 \( 8 \times 10^{-7} \text{ A/cm}^2 \). 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 \( \sim 30 \text{ fF} \). The optimum response is represented by a junction capacitance \( C_J = 98 \text{ fF} \), a depletion region capacitance \( C_R = 98 \text{ fF} \), and a series resistance \( R_S = 100 \Omega \), and series 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 \( \leq R_L \leq 25 \Omega \). A series resistance \( R_L = 10 \Omega \) 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 \( R_L \). In addition, our analysis neglects that a fraction of the photocarriers are...
todiodes are now being used in commercial optical receivers. Typically, a photodiode measures 100 fF of capacitance, 90 pA of leakage current, 73% external quantum efficiency, <2% reflectivity, and a 22-GHz bandwidth. A transit time of ~10 ps ensures a reasonable simulation of the bandwidth data. These photodiodes are now being used in commercial optical receivers.

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_0.27Ga_0.73As/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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