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


Abstract—We report on the design, fabrication, testing, and modeling of single-heterojunction $\text{Al}_{0.27}\text{Ga}_{0.73}\text{As}/\text{GaAs}$ p-i-n photodiodes for...
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 f3dB 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 Al0.34Ga0.66As/GaAs p-i-n photodiodes with f3dB ~ 22 GHz and external quantum efficiency η = 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 Al0.34Ga0.66As:Be window layer allows for wavelength coverage between 700 and 870 nm. We use a mesa structure with an active area of ~1100 μm². 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, ~2 × 10¹⁸ cm⁻³), a 2.0-μm GaAs i layer (undoped p-type, <10¹⁷ cm⁻³) and a 1-μm Al0.34Ga0.66As:Be window layer (p-type, ~2 × 10¹⁸ 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 800-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 × 10⁻⁶ A/cm². 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.

At 850 nm, the photodiodes have a typical measured external quantum efficiency η = 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 (η = 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 f3dB 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 Cj = 98 fF, a depletion region resistance R0 = 100 MΩ, and series resistance Rs. The diode package is represented by a package capacitance Cp = 25 fF and a package inductance Ls = 0.1 nH. We assume a load resistance Rs = 50 Ω. 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 ≤ Rs ≤ 25 Ω. A series resistance Rs = 10 Ω 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 Rs. In addition, our analysis neglects that a fraction of the photocarriers are
REFERENCES


