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

C. Johnsen, S. Sloan, D. Braun, J. L. Russell, M. Zurakowski,
M. Lightner, F. Kellert, G. Patterson, R. Koo, D. Derickson,
and J. Bowers

***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**

Manuscript received July 3, 1990; revised February 1, 1991. The review of this brief was arranged by Associate Editor G. Craford.

C. Johnsen, S. Sloan, D. Braun, M. Zurakowski, M. Lightner, F. Kellert, and G. Patterson are with the Microwave Technology Division, Hewlett-Packard Company, Santa Rosa, CA 95403.

J. L. Russell was with the Microwave Technology Division, Hewlett-Packard Company, Santa Rosa, CA 95403. He is now with the Department of Electrical Engineering, Ohio State University, Columbus, OH 43206.

R. Koo is with the Signal Analysis Division, Hewlett-Packard Company, Rohnert Park, CA 94928.

D. Derickson and J. Bowers are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106.

IEEE Log Number 9100806.

0018-9383/91/0800-1968$01.00 © 1991 IEEE

use as components in optical receivers. The photodiodes are grown by molecular beam epitaxy and fabricated as 1100-μm^2 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 ~ 1100 μm^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, 2×10^{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 8×10^{-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.

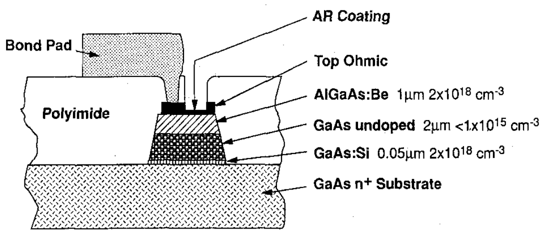

Fig. 1. Schematic diagram of the single-heterojunction $Al_{0.27}Ga_{0.73}As$/GaAs p-i-n photodiode.

TABLE I
RESULTS FOR AlGaAs/GaAs p-i-n's REPORTED IN THE LITERATURE

GaAs Substrate	Design	f_{3dB} (GHz)	External η (%)	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 $R_D = 100$ MΩ, 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 $R_L = 50$ 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: $0.5 \leq R_S \leq 25$ Ω. A series resistance $R_S = 10$ 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 R_S. In addition, our analysis neglects that a fraction of the photocarriers are

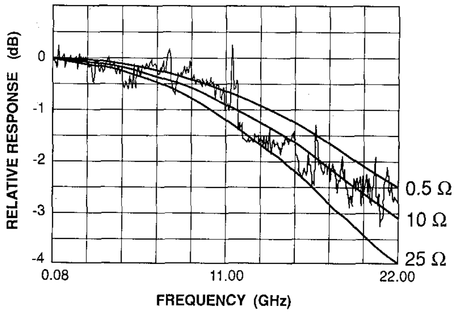

Fig. 2. Spectrum analyzer measurement of photodiode bandwidth. High-frequency circuit simulations of the photodiode are shown as solid lines for: $R_S = 0.5$, 10, and 25 Ω.

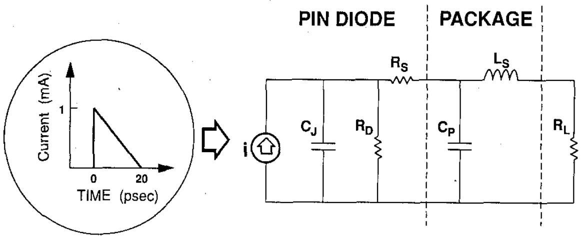

Fig. 3. Photodiode circuit model used for high-frequency circuit simulations. The inset shows a triangular current pulse of 20-ps duration.

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.

Acknowledgment

The authors gratefully acknowledge fabrication work by M. Stone, C. Conner, and M. Planting, and helpful conversations with K. Chan, S. Y. Wang, R. Bray, and C. Stolte.

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