108-GHz GaInAs/InP p–i–n Photodiodes
with Integrated Bias Ties and Matched Resistor

Yih-Guei Wey, Kirk S. Giboney, Student Member, IEEE, John E. Bowers, Fellow, IEEE, Mark J. W. Rodwell, Member, IEEE, Pierre Silvestre, Prabhu Thiagarajan, and Gary Y. Robinson

Abstract—Connections to bulk bias tees and various mismatched loads degrade the usable frequency response of high-speed photodetectors. Monolithic integration of passive components to enhance the realizable performance of high-bandwidth, long-wavelength photodiodes is demonstrated. Circuits having bias tees and matched resistors integrated with 7-μm × 7-μm photodiodes show usable electrical bandwidths exceeding 100 GHz.

INTRODUCTION

Efficient wide-bandwidth photoreceivers demand optoelectronic integration to achieve the required performance in practical configurations. In instrumentation applications, it is necessary to obtain a smooth, wide-band response with various loads. Integrated bias ties can circumvent limitations on usable bandwidth caused by external bias ties. A matched-source resistor can decrease frequency response variations by reducing the source reflection coefficient, and it can increase the resistance-capacitance (RC) bandwidth limitation by presenting a lower effective load resistance to the photodetector [1]. We report here the integration of high-speed, long-wavelength photodiodes with bias ties and matched resistors, yielding greater than 100-GHz bandwidth with high efficiency.

The integrated circuit design is shown, together with external connections, in Fig. 1. The bypass diode area is about 20 times the photodiode area and serves the function of a shunt capacitor. Its purpose is to provide a short circuit at frequencies of interest while supporting a dc voltage. A reverse-biased diode is used rather than an insulator—capacitor because it can be implemented without additional process steps and gives a higher yield. The capacitance can be precisely controlled via lithography and epitaxially grown layers. By implementing this element monolithically, it is possible to present a net load impedance to the photodiode essentially equal to the transmission-line characteristic impedance over the design frequency range.

The voltage at the load $Z_{L}$, in the circuit shown in Fig. 1, is

$$v_{\text{meas}} = i_{\text{phot}}Z_{0} \cdot \frac{R_{S}}{R_{S} + Z_{0}} \cdot \frac{1}{1 - \frac{\Gamma_{1} e^{-2j\beta l}}{\Gamma_{2}}} \quad (1)$$

where $\Gamma_{1}$ and $\Gamma_{2}$ are the source and load reflection coefficients, $\beta$ is the propagation constant, and $l$ is the length of the transmission line connecting the source and load. Since $\beta$ is a function of frequency, resonances will result from the reflections at the source and load, depending on the product of the reflection coefficient magnitudes.
in the third term. The matched source resistor greatly reduces $\Gamma_s$, so frequency response variations are suppressed. This resistor, which is formed in the n-InP layer without additional process steps, also doubles the ideal $RC$ bandwidth limitation since it cuts the net load presented to the photodiode in half, as expressed by the second term. However, since the resistor forms a current divider with the load, the effective quantum efficiency is also cut in half.

Circuits using 7-$\mu$m-square photodiodes with bias tees are fabricated with and without matched resistors. Also built are 2-, 3-, 4-, 5-, and 30-$\mu$m-square photodiodes without bias tees or matched resistors. The devices have 200-nm-thick Ga$_{0.47}$In$_{0.53}$As absorption layers. Fig. 2 shows the layout of a circuit including bias tee and matched resistor. The bypass diode and matched resistor are placed close to the photodiode so these elements may be regarded as lumped over the design bandwidth.

**MEASUREMENTS AND ANALYSIS**

Fig. 3 shows measurements of the reflection coefficients of devices with and without matched resistors to 40 GHz. $|\Gamma_s|$ is less than $-15$ dB with and $-1.9$ dB without the matched resistor over the measurement range. Thus, the voltage standing wave ratio is improved from 9.2 to 1.4 up to 40 GHz by including the matched resistor.

Time-domain optical responses are measured by pump-probe electrooptic sampling, using the InP substrate as the electrooptic modulator [6]. A passively mode-locked Ti:sapphire laser delivering pulses with 200-fs autocorrelation full-width at half-maximum (FWHM) and 972-nm center wavelength is used as the measurement source, and the pump and probe beams are focussed through the back side of the wafer. The overall system time resolution is subpicosecond in this arrangement for the given geometries. The devices are contacted by microwave probes, and a 50-GHz sampling oscilloscope monitors device output while providing a 50-$\Omega$ ac termination. A 40-GHz external bias tee is used with those devices without integrated bias tees.

Electrooptically measured responses of 2-$\mu$m $\times$ 2-$\mu$m photodiodes without integrated bias tees or matched resistors, and 7-$\mu$m $\times$ 7-$\mu$m photodiodes with integrated bias tees, with and without matched resistors, under 3-V reverse bias are shown in Fig. 4(a). The 2-$\mu$m device response is 3.3 ps FWHM. The 7-$\mu$m device with matched resistor is seen to have a 3.8-ps FWHM response, and the device without matched resistor shows a 4.6-ps FWHM response. Note that the shapes of the tails suggest a more dominant RC time component in the response of the 7-$\mu$m device without matched resistor. The frequency responses plotted in Fig. 4(b) are found from the Fourier transforms of the corresponding time responses in Fig. 4(a). The 3-dB electrical bandwidth of the 2-$\mu$m device is 110 GHz, and the 7-$\mu$m devices have bandwidths of 108 GHz and 62 GHz, with and without matched resistors.

The bandwidths of various sizes of photodiodes on the same wafer, biased at 3 V, are plotted along with model predictions for devices without matched resistors as a function of area in Fig. 5. The fastest device is the 4-$\mu$m$^2$ photodiode, which shows FWHM time responses as short as 3.0 ps and bandwidths as high as 110 GHz. Notice that the 49-$\mu$m$^2$ photodiode with bias tee and matched resistor, and the 4- and 9-$\mu$m$^2$ discrete photodiodes all have bandwidths nearly equal, since they approach the 140-GHz calculated transit-time limit.
Fig. 4. (a) Electrooptically measured optical time response of 7-μm × 7-μm photodiodes with integrated bias tees, with and without matched resistors under 3-V reverse bias, and (b) corresponding electrical frequency responses from Fourier transforms.

Fig. 5. 3-dB electrical bandwidth versus photodiode area from measurements (filled squares) and model (line).

The external quantum efficiency as measured on 30-μm × 30-μm photodiodes is 50% at 0.97-μm wavelength and 32% at 1.31-μm wavelength. The antireflection (AR)-coating center wavelength is 1.3 μm. Enhanced efficiency results from a second pass after reflection from the p-contact metal. The quantum efficiency can be calculated by

\[ \eta = (1 - R) \cdot \left( 1 + R_{pc} e^{-a \cdot d} \right) \cdot (1 - e^{-a \cdot d}) \]  

(2)

where \( R \) is the reflectivity at the air-substrate interface, \( R_{pc} \) is the p-contact reflectivity, \( \alpha \) is the absorption coefficient, and \( d \) is the depleted thickness of the absorption layer. The experimental efficiencies agree well with values calculated using measured values for \( R \), assuming \( R_{pc} = .67 \), and using measured absorption coefficients from [7].

Since these devices are illuminated from the n-side, the fractional hole contribution to the photocurrent will decrease as wavelength increases. Thus, it is expected that the bandwidths would be at least as great at 1.3-μm wavelength as the values measured at 0.97 μm. Assuming efficient focusing into the small areas, the 2-μm × 2-μm and 3-μm × 3-μm devices would have bandwidth–efficiency products of 35 GHz at 1.3 μm. The bandwidth–efficiency product of the circuit using a 7-μm × 7-μm photodiode with bias tee and without matched resistor is 20 GHz, but the bandwidth–efficiency product of the same circuit with matched resistor is only 17 GHz because of the loss of half of the photocurrent in the matched resistor.

SUMMARY AND CONCLUSIONS

High-speed, high-efficiency GaInAs/InP p-i-n photodiodes are fabricated and monolithically integrated with bias tees and matched resistors to enhance their usable frequency response. Electrical bandwidths greater than 100 GHz are measured for the smaller photodiodes and for circuits using 7-μm × 7-μm photodiodes with bias tees and matched resistors. External quantum efficiency of 32% at 1.3-μm wavelength is measured on large-area devices. Simple methods for including passive components to enhance the performance of high-speed photoreceivers are demonstrated. Such methods could be more generally applied to integrate filters, matching networks, coupling structures, and other functions in optoelectronic integrated circuits (OEIC's).

ACKNOWLEDGMENT

The authors thank T. Reynolds for depositing the AR coatings.

REFERENCES


