High Speed Optical Detectors for Monolithic Millimeter Wave Integrated Circuits

K. Litvin, J. Burm, D. Woodard, W. Schaff, and L. F. Eastman

School of Electrical Engineering, Cornell University, Ithaca, NY 14850

ABSTRACT

Metal-semiconductor-metal photo diodes with interdigitated Schottky barrier fingers are being developed for applications in monolithic optical receiver circuits with the purpose of detecting millimeter wave modulation signals being transmitted via an optical carrier. The devices are planar and incorporate submicron finger spacings and a thin absorption region for speed with a buried stack of tuned Bragg reflectors for enhanced sensitivity at the carrier wavelength. These devices are being integrated with short-gate MODFET amplifiers to form the complete monolithic integrated optical receiver circuit.

DEVICE DESCRIPTION

Metal-semiconductor-metal photo diodes with interdigitated Schottky barrier fingers are being fabricated in the AlGaAs material system using electron beam lithography techniques (Fig. 1). The photo detectors are capable of detection bandwidths in excess of 100 GHz [1-3]. The devices have a planar construction making them ideal candidates for monolithic integration [4,5]. The detector structures were designed with the aid of a computer program and then grown by molecular beam epitaxy. The photo diodes in this design incorporate sub-micron electrode spacings and a thin absorption layer of GaAs, these features limit the transit time of the optically generated carriers thus providing the mechanism for millimeter frequency operation (Fig. 2).

Device sensitivity to low intensity light is enhanced with the inclusion of a highly reflective (99%) stack of tuned Bragg reflectors buried below the absorption layer. The Bragg reflector stack is composed of nonabsorbing alternating quarter wavelength layers of $Al_{0.9}Ga_{0.1}As$ and $Al_{0.35}Ga_{0.65}As$. The reflective stack causes incident photons, of the appropriate wavelength, to make a second pass through the absorption layer thus creating additional carriers for collection at the electrodes. Additional sensitivity refinements were made by including a top surface optical impedance matching layer of $Al_{0.35}Ga_{0.65}As$. This layer reduces top surface reflectance to nearly negligible values (0.5%). The interfaces between the GaAs absorption layer and the matching layer above it and the bottom of the absorption layer and the top surface of the Bragg reflector stack also form a potential energy well for the photo generated carriers. This is due to the energy band discontinuity of the material layers. The potential energy well serves to confine the photo generated carriers to the thin absorption region where they can be rapidly collected by the electrodes on the top surface. (Also prevents carrier loss by rapid surface recombination (v_s @ $3x10^6$ cm/sec)). The combined effects of the finite line width of the Bragg reflector stack, absorption layer and top surface matching layer introduces some wavelength discrimination capability into the device because there is an increased optical sensitivity at the design wavelength and a decreased sensitivity at other wavelengths away from this line (Fig. 3).

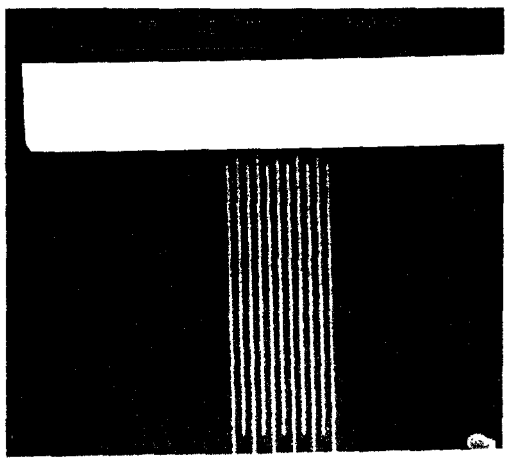

Figure 1. A MSM Photodiode with 0.25 μm finger and 0.75 μm gap. Ti 150 Å, Pd 150 Å and Au 500 Å are used for the finger metalization. The pad connecting the fingers is part of a coplanar waveguide

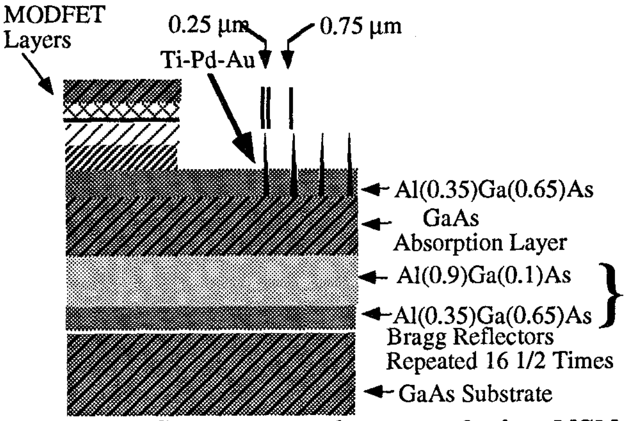

Figure 2. Cross-sectional view of the MSM photodiode material structure showing the top surface impedance matching layer, absorption layer, and Bragg reflector stack.

EXPERIMENTAL RESULTS

The passive components of the detector equivalent circuit model were determined using an HP8510 network analyzer (Fig. 4) . Detector diodes having eleven fingers 23 µm long, 0.5 µm wide and 1.0 µm gaps between the fingers had capacitance values ranging from 16 to 18 fF with 1 to 5 ohm internal series resistance in the fingers and greater then 1 megaohm parallel resistance across the fingers. For a 50 ohm load resistor the RC cut off frequency ranged from 160 to 180 GHz.

Static optical tests were done with a white light source and monochromator in order to characterize the spectral response of the diodes. The response signal was normalized to the white light spectrum (Fig. 5). A large size detector was used in the experiment for better sensitivity. Figure 5 shows that the expected peak in the response for a 800 nm wafer design was down-shifted slightly, this probably indicates that the angle of incidence was not quite normal to the sample. Photospectrometer measurements of the wafer reflectance support this conclusion.

Optical measurements using a short pulse (120 fs) mode locked laser operating at 780 nm with a beam diameter of 10 µm indicated a carrier transit time limited bandwidth in excess of 40 GHz (this was the limit of the measurement system). The detector response was observed using a HP2782 spectrum analyzer. The measurement on a detector diode with 23 µm long fingers, 0.5 µm finger width and 0.5 µm gap between the fingers fabricated on a GaAs wafer designed for 750 nm light had the following results: At 7 volts applied bias and 80 mW average incident power, it showed a flat response up to at least 40

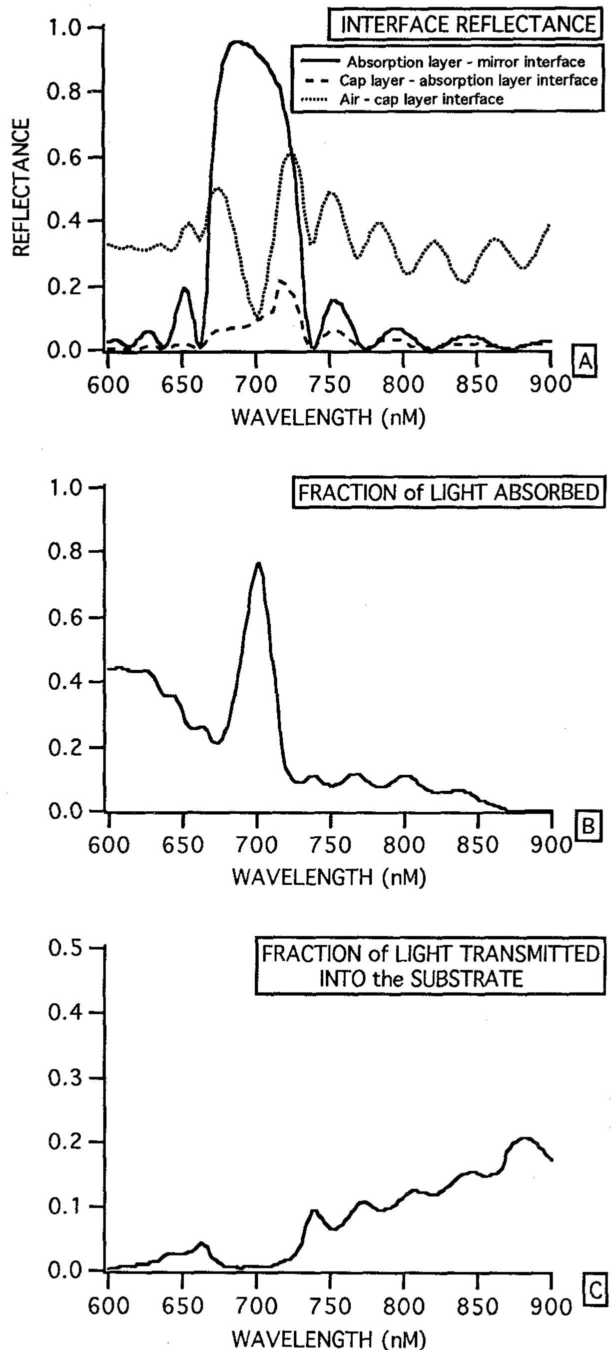

Figure 3. Calculated optical response of the detector material layers for a 700 nm light design:
A reflectance at important interfaces of the structure. B fraction of incoming light absorbed.
C fraction of incoming light transmitted into the substrate.

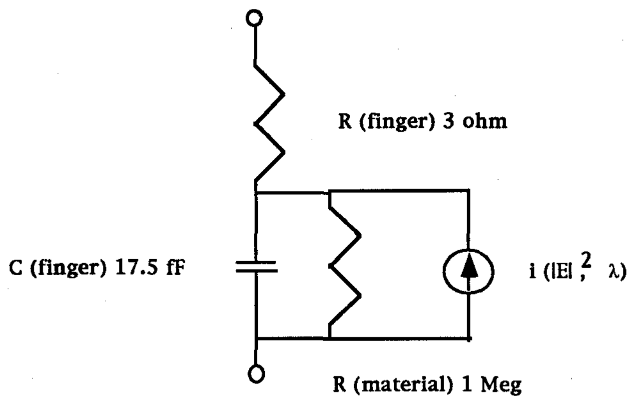

Figure 4. MSM detector diode equivalent circuit model.

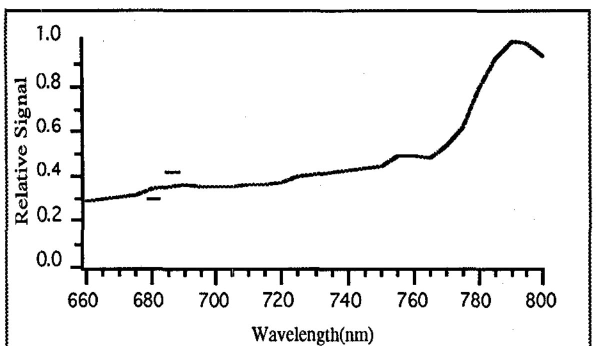

Figure 5. Relative signal from a detector vs. optical wavelength. The detector was fabricated on a wafer designed for light at a wavelength of 800 nm.

GHz. When the average incident light power was doubled to 160 mW the response at 39 GHz was -6 dB down due to excess carrier generation. The dynamic range of the detectors was then measured using a Ti:sapphire laser operating at 770 nm with a variety of neutral density filters . The dynamic range was found to be 33 dB.

Optical measurements employing a semiconductor mode locked laser as a short pulse optical source were also performed and the detector response was observed in the time domain using a sampling oscilloscope. The full width half maximum of the output pulse was 15 ps. This value was again essentially the limit of the measurement system's capability.

DEVICE INTEGRATION

The MSM photodiodes are being integrated with short-gate MODFETs for use as monolithic integrated optical receiver circuits capable of detecting a 44 GHz modulation signal being transmitted via an optical carrier (Fig 6.) [6]. The transisor layers are grown on top of the detector layers in the MBE system. A slow etch-rate citric acid solution is used for the transistor mesa isolation. The wafer top surface reflectance is monitored with a photospectrometer until the reflectance minima shifts to the design wavelength. The MODFETs will be used as low noise amplification devices in the optical receiver circuits. The current transistor design has a source-drain spacing of 2 μm with a gate length of 0.25 μm and gate width of 100 μm. We are in the process of developing a transistor with a gamma-gate and self-aligned ohmic metalization in order to reduce the source resistance and therefore improve the noise and frequency characteristics of the devices [7,8]. In test structures we have achieved gates with 0.25 μm footprint and 0.6 μm cross-section along the top. The gate had an overhang ratio of more then 2:1 and a source-drain spacing of 0.6 μm. With self-aligned metalization the source-gate spacing was 0.1 μm and the drain-gate spacing was 0.25 μm (Fig. 7). Coplanar waveguide interconnections are being used in the circuit design.

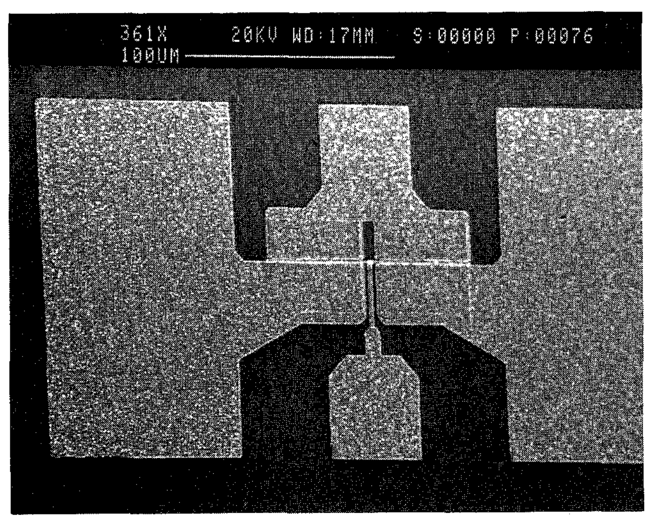

Figure 6. Typical MODFET with 100 μm gate width and 0.25 μm gate length.

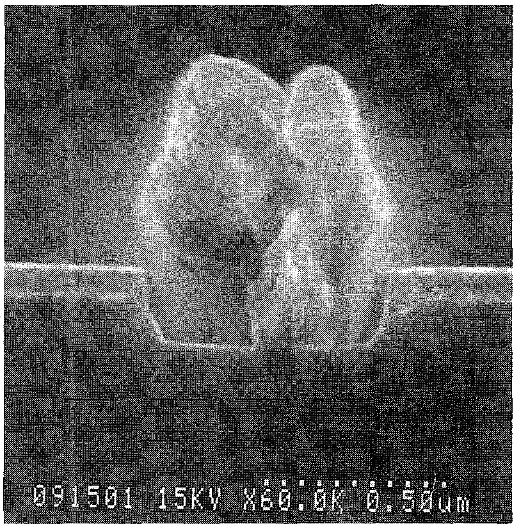

Figure 7. Gamma-gate with 0.25 μm footprint and 2:1 overhang ratio. The photograph also shows the 0.6 μm drain - source spacing after the self-aligned ohmic metalization step.

SUMMARY

Metal-semiconductor-metal photodetector diodes have been designed with the aid of a computer program. The material was grown by MBE and the devices were fabricated with electron beam lithography. The detectors incorporate features for high speed operation, (submicron electrode spacings, thin absorption layer, and a potential well to confine optically generated carriers to the absorption layer), with features to enhance the device sensitivity, (buried Bragg reflector stack, and a top surface optical impedance matching layer). Device measurements indicate top surface reflectance of 0.5% with an operation bandwidth in excess of 40 GHz and a dynamic range of 33 dB. The devices are being integrated with short-gate MODFETS for applications in monolithic millimeter wave optical receiver circuits.

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