Paper

Photovaractor performance for optically controlled microwave circuits

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Abstract — The photovaractor for optically controlled microwave circuits was designed and studied. The photovaractor module was fabricated as a planar *p-i-n* photodiode chip placed in a fibre optic matching receptacles. Study of *C-V* characteristics in the light illumination mode has shown that capacitance characteristics are strongly dependent on the light illumination power. These variations of the photovaractor diode capacitance are large enough to be used in optically controlled circuits such as oscillators, mixers and switchers.

Keywords — circuits, photovaractor, optically controlled.

1. Introduction

Various varactor diodes are extensively used in microwave applications, which include phase shifter, frequency multiplier, mixer and nonlinear transmission-line [1 – 4]. In recent years the application of photonic devices for such optically controlled microwave circuits are discussed widely in literature [5 – 9]. The advantages of optical control are high tuning speed and good isolation between controlling and microwave signals.

One of optical control means is the use of junction capacitance variation due to optical illumination. We propose to call such a device as the photovaractor. In this paper we report measurements of photovaractor fabricated as a planar *p-i-n* InP/InGaAs photodiode placed in a fibre optic matching receptacle. Variation of the photovaractor characteristics due to optical illumination with different light power are studied.

2. Photovaractor diode

The photovaractor described in this paper is a planar *p-i-n* photodiode with front illuminated p^+-region and back ohmic contact to n^+-InP substrate. The *p-i-n* photodiode has been fabricated in *n*-InP/*n*-InGaAs/n^+-InP heterostructure which was grown on a substrate by low pressure metal-organic vapour-phase epitaxy (LP-MOVPE). The heterostructure has been studied using electrochemical *C-V* profiling method before making the photodetector chip. Figure 1 shows the cross-section of the planar InP/InGaAs *p-i-n* photodiode. The epitaxial layer is composed of 0.6 μm, $1.2 \cdot 10^{15}$ cm^{-3} undoped *n*-InP top layer, 1.5 μm, $1.2 \cdot 10^{15}$ cm^{-3} undoped *n*-InGaAs absorption layer, 0.5 μm undoped *n*-InP buffer layer on 400 μm, $3 \cdot 10^{18}$ cm^{-3} Te doped n^+-InP substrate. The Hall method measurement has given following majority carrier mobility values in InGaAs absorption layer: 7735 cm^2/V·s at 300 K, and 64084 cm^2/V·s at 78 K.

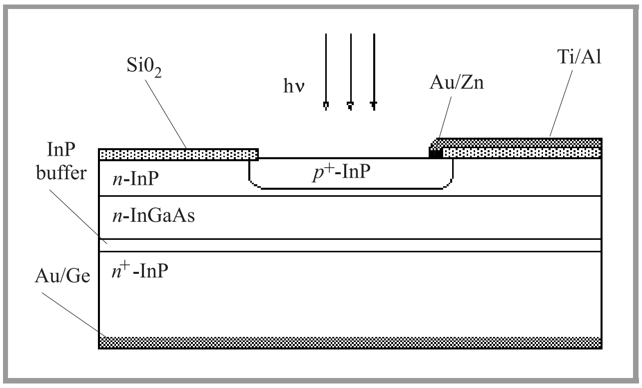

Fig. 1. Cross-section of the planar InP/InGaAs *p-i-n* photovaractor.

The p^+-region was formed by local diffusion of Zn into the wide band gap *n*-InP top layer. The Zn diffusion was performed in an open gas flow system into unpassivated InP surface at 470°C [10]. The results of electrochemical *C-V* measurements indicated that the average doping level in the p^+-InP layer for this diffusion conditions was $7.5 \cdot 10^{18}$ cm^{-3}, and the layer thickness was 0.5 μm. SiO$_2$ films of 0.25 ± 0.01 μm thickness were used as diffusion mask and passivative layer for the planar diode structure. These films have been made by pyrolysis of tetraethoxysilane at $330 - 350$°C in O$_2$/N$_2$ flow. Ohmic contacts to p^+- and n^+-regions were formed using AuZn and AuGe binary alloys, respectively. Contact annealing was performed at 350°C in H$_2$ flow. Contact resistance for both p^+- and n^+-regions was $1 - 3 \cdot 10^{-6}\ \Omega \cdot \mathrm{cm}^2$. The diameter of the photosensitive area was 100 μm.

The photovaractor module has been fabricated as a planar *p-i-n* photodiode chip placed in a fibre optic matching receptacle. To reduce reflection from the fibre-air, air-optics and air-chip boundaries, a special matching medium having a refractive index close to that of quartz fibre was used [11].

3. Results and discussion

Measurements of *I-V* characteristics of the photovaractor have shown that the breakdown voltage was 50 V. The values of dark current were $3.5 - 3.7 \cdot 10^{-9}$ A under 1.0 V reverse bias, and $4.0 - 4.1 \cdot 10^{-9}$ A under 15 V bias. Capacitance variation with bias voltage in dark condition is shown in Fig. 2. The measurements were carried out with LCG-meter at 1 MHz. One can see that with the bias voltage variation the capacitance change is small and the ratio $C_{\max}/C_{\min}$ is equal to 2.35. Frequency measurements were carried out using 1300 nm semiconductor laser with 2.5 mW power as a source. Spectral analyser with the bandwidth from 0.4 GHz up to 3.0 GHz was used as a receiver in the source-detector system. The receptacled *p-i-n* photodiode module with 50 Ω matching resistors has the bandwidth over 1.5 GHz.

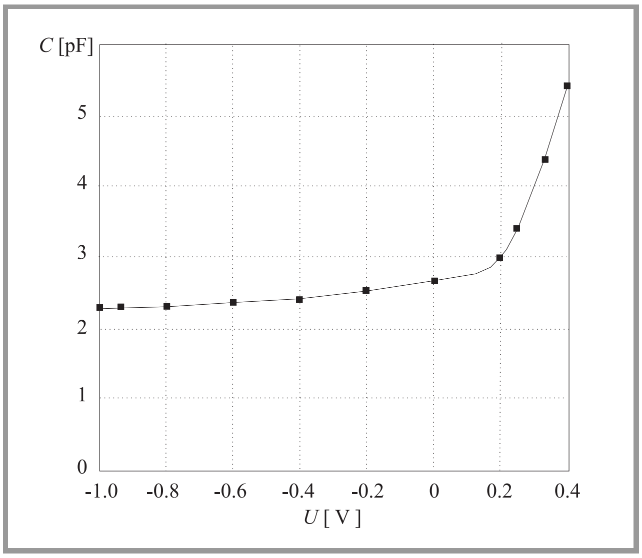

Fig. 2. *C-V* characteristic of the photovaractor in dark condition.

Figure 3 presents the response of the photovaractor module measured in the 700 – 1800 nm range in bias free conditions. The photovaractor module response is 0.75 ± 0.05 A/W at wavelength 1300 nm. It is necessary to note that the response is not changed under reverse bias voltage variation. This fact gives us the possibility to conclude that the depleted region of *p-i-n* junction penetrates through the absorption InGaAs layer down to the buffer layer and photocarriers are collected completely even in the bias free conditions.

Figure 4 shows *I-V* characteristics of the photovaractor under different optical power illumination. It can be seen that the photovaractor has linear response up to 750 μW optical power in the bias free conditions.

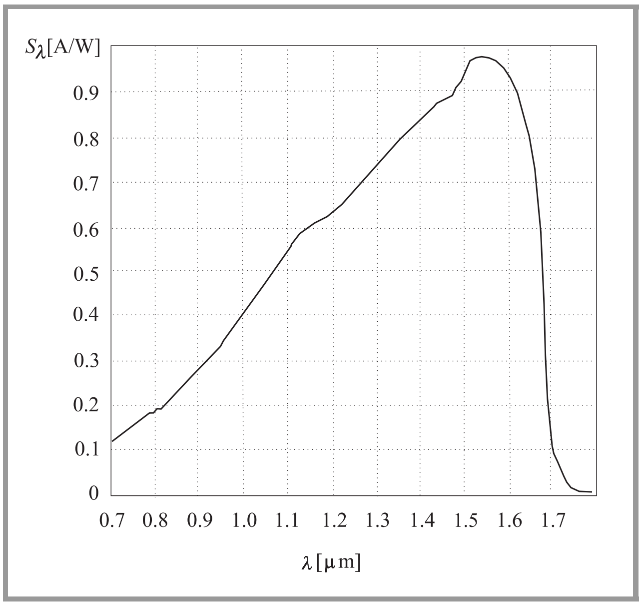

Fig. 3. Spectral response of the photovaractor.

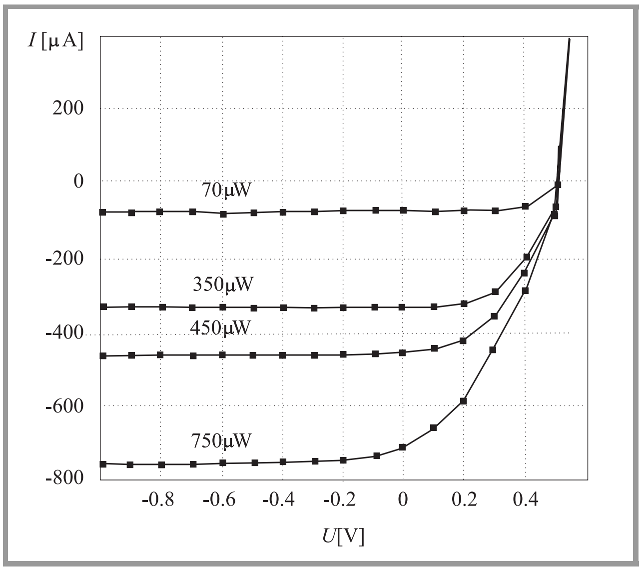

Fig. 4. *I-V* characteristics of the photovaractor under different optical power.

Photovaractor's capacitance can be strongly modified by optical illumination. Figure 5 shows the capacitance variation versus optical illumination power under different bias voltages. In the dark condition we have usual a decrease of the diode capacitance with the reverse bias voltage because the diode's depleted region width slightly increases. The depleted region width decreases significantly with the optical power increase and this results in the increasing capacitance. The ratio $C_{\max}/C_{\min}$ depends on the variation range of the optical power and bias voltage (Fig. 5). For example, at the bias voltage $+0.1$ V the capacitance changes from $C_{\min}$ = 2.75 pF up to $C_{\max}$ = 69 pF under the optical power variation from zero to 400 μW, i.e. the ratio $C_{\max}/C_{\min}$ is equal to 25. At the bias voltage -0.4 V and optical power variation from zero up to 750 μW the ratio $C_{\max}/C_{\min}$ decreases to 15. It is necessary to note that the capacitance nonlinearity increases when the optical power is increased. For example, under the bias -0.4 V and optical power variation from zero up to 400 μW the ratio $C_{\max}/C_{\min}$ is equal to 2, and it increases to 15 under the extension of optical power variation range up to 750 μW.

Analysis of capacitance change under different conditions gives the possibility to choose the optimum operation regime of the photovaractor. It seems that the best one is

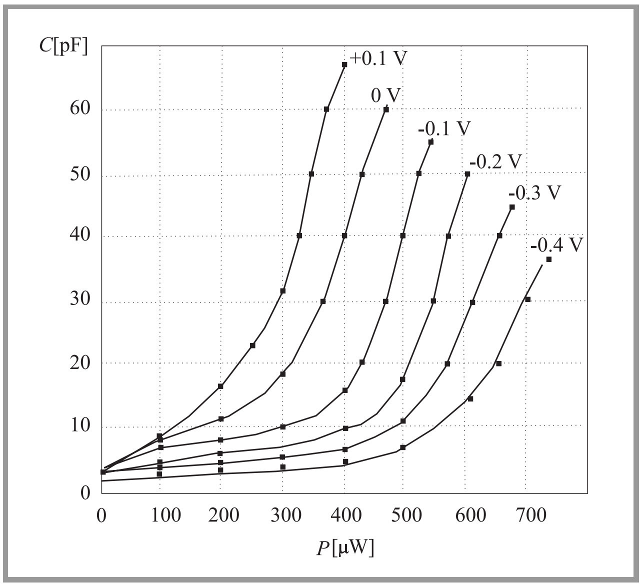

Fig. 5. The capacitance versus optical illumination power variation under different bias voltages.

near bias free region because the photovaractor has wide junction capacitance variation range due to illumination, as well as good sensitivity, frequency bandwidth and low dark current.

4. Conclusions

The receptacled *p-i-n* photovaractor module incorporating the matching medium are presented. The study of *C-V* characteristics in the light illumination mode has shown that the capacitance characteristics are strongly dependent on the light illumination power. These junction capacitance variations of the photovaractor diode are large enough to be used in optically controlled microwave circuits such as oscillators, mixers and switchers.

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