PAPER

Equivalent Circuit Model of InAlAs/InGaAs/InP Heterostructure Metal-Semiconductor-Metal Photodetectors

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SUMMARY One-dimentional equivalent circuit model of a heterostructure InAlAs/InGaAs/InP metal-semiconductor-metal photodetector is discussed. In this photodetector, InGaAs is used as an optical absorption layer and the InAlAs is used for Schottky barrier enhanement. The measured S_{11} parameter deviates from equi-resistance lines on the Smith chart, indicating the equivalent circuit is different from the conventional equivalent circuit using a series resistance, a depletion region capacitance and a depletion region resistance. The difference is due to band discontinuity at the heterojunctions, and we propose a equivalent circuit taking account of the band discontinuity. The band discontinuity is expressed by parallel combination of a resistance and a capacitance. The measured S_{11} parameter can be fitted well with the calculated S_{11} parameter from the proposed equivalent circuit, and we can successfully extract the device parameters from the fitted curve.

key words: *metal-semiconductor-metal photodetector, heterostructure, S parameter, equivalent circuit*

1. Introduction

Metal-Semiconductor-Metal photodetectors (MSM-PDs) are very attractive optical devices in optical communication systems because of wide bandwidth, easy fabrication, and easy monolithic integration with FETs/HEMTs [1]–[3]. In short wavelength range, low-temperature-grown GaAs (LT-GaAs) is used as an optical absorption layer, and the bandwidth more than 100 GHz is achieved [4], [5] because of ultra-fast optical response of the LT-GaAs. In long wavelength range, InGaAs is used as an optical absorption layer, and InAlAs is used for Schottky barrier enhancement layer as shown in Fig. 1 because it is difficult to achive good Schottky contanct on InGaAs due to large electron affinity [6]–[8]. In the InAlAs/InGaAs/InP MSM-PD, heterojuctions are formed between the InGaAs and the InAlAs layers, at which photo-generated carriers are trapped, which degrades bandwidth.

The frequency bandwidth of photodetectors is determined by both the CR-limited bandwidth estimated from the equivalent circuit model and the carrier transit time-limited bandwidth. In the equivalent circuit model, used to date, to estimate the CR-limited bandwidth, a depletion region capacitance, a series resistance and a load resistance are used. The equivalent circuit is basically applicable to photodetectors with a homogeneous material such as Si photodetectors. This paper describes an one-dimensional equivalent circuit model of MSM-PDs taking account of the heterostructure [9]. In Sect. 2, the structure and the fabrication process are briefly explained. In Sect. 3, the measured results of the S_{11} parameter along with the I–V and the C–V characteristics are shown. In Sect. 4, we propose an equivalent circuit model of the heterostructure MSM-PD to describe the measured S_{11} parameter, and device parameters are extracted from the measured S_{11} parameter and the equivalent circuit. And we conclude our paper in Sect. 5.

2. Structure and Fabrication

The cross-sectional view of the MSM-PD is shown in Fig. 1. The layer structure consists of a 200-nm-thick

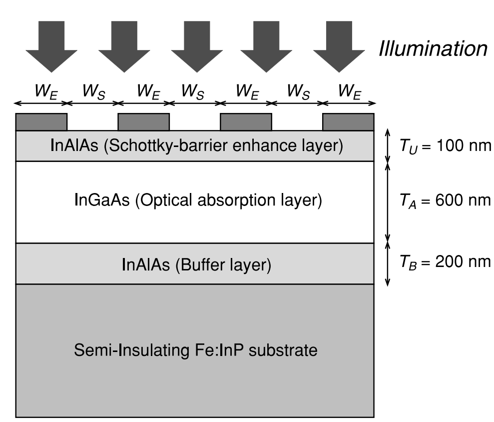

Fig. 1 Cross-sectional view of the fabricated MSM-PD. W_E and W_S are the electrode width and the electrode separation, respectively.

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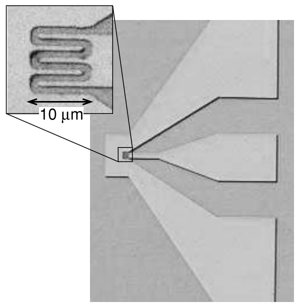


Fig. 2 Photograph of the fabricated MSM-PD.

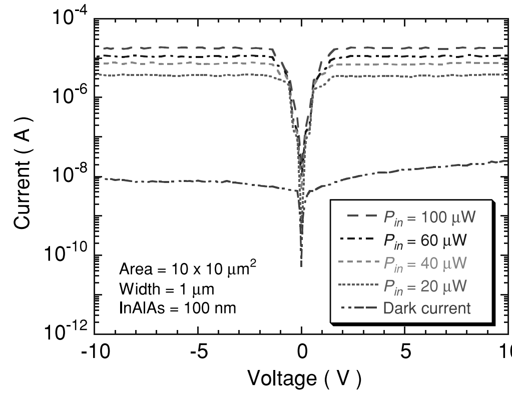


Fig. 3 Measured I–V characteristics for $W_E = W_S = 1\,\mu$m and the detection area of $10\,\mu$m × $10\,\mu$m.

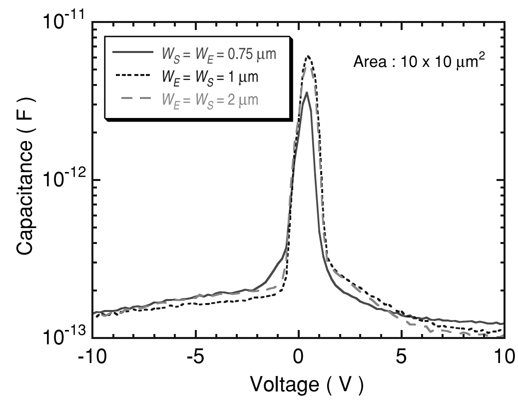


Fig. 4 Measured C–V characteristics for different values of W_E and W_S. The detection area is $10\,\mu$m × $10\,\mu$m.

InAlAs buffer layer, a 600-nm-thick InGaAs absorption layer, and a 100-nm-thick InAlAs Schottky-barrier-enhancement layer on a semi-insulating InP substrate. Interdigitated anode and cathode electrodes are formed on the surface with a 100-nm-thick Nickel by liftoff technology, and the light is illuminated onto the interdigitated area, which is the photodetection area. Both the anode and the cathode electrodes are Schottky-contacted to the InAlAs layer. No graded composition layer nor intermediate composition layer is inserted between the InGaAs and the InAlAs layers to relax the band discontinuity.

Figure 2 shows the photograph of the fabricated MSM-PD. The detection area is $10\,\mu$m × $10\,\mu$m, and both the electrode width and the electrode spacing are $1\,\mu$m. The detection area is surrounded by metal to avoid optical absorption outside the detection area.

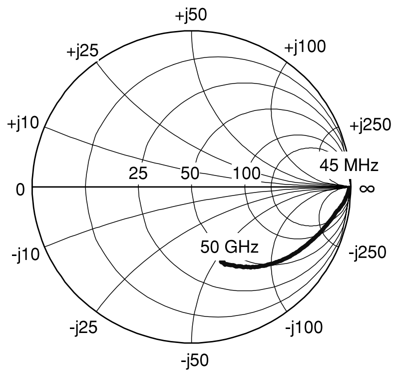
3. Electrical Property

Figure 3 shows the measured I–V characteristics of the MSM-PD at $1.55\,\mu$m wavelength. The dark current rapidly increases with the bias voltage below 2 V, and then almost saturates above 2 V bias voltage. The dark current is 25 nA at 10 V bias. Figure 4 shows the measured C–V characteristics at 1 MHz for different electrode widths and spacings. The large capacitance at the low bias voltage is attributed to insufficient depletion in the InGaAs layer. The capacitance slightly depends on the electrode width and the spacing. The capacitance is about 110 fF at 10 V bias.

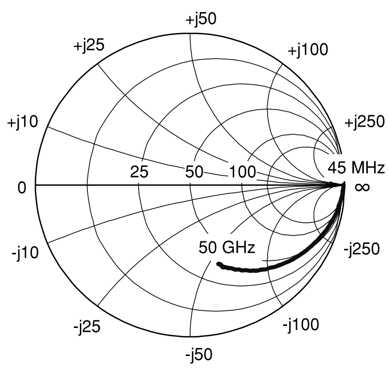
Figure 5 shows the measured S_{11} parameter from 45 MHz to 50 GHz. The measured S_{11} parameter deviates from equi-resistance lines. In the conventional simple equivalent circuit mode, only a depletion capacitance C_D, a depletion resistance R_D and a series resistance R_S are used as shown in Fig. 6(a). An example of the S_{11} parameter is shown in Fig. 6(b) with $C_D = 100$ fF, $R_D = 1\,\mathrm{M}\Omega$ and $R_S = 25\,\Omega$, showing that the S_{11} parameter changes along the equi-resistance line. The measured S_{11} parameter is quite different from Fig. 6(b). This means the equivalent circuit of the fabricated MSM-PD is different from Fig. 6(a).

4. Equivalent Circuit Model

In the MSM-PD shown in Fig. 1, photo-generated carriers travel in lateral direction, and heterobarriers are distributed along the heterojunction. Here we approximate the MSM-PD as an one-dimensional form shown in Fig. 7(a), and its equivalent circuit model is shown in Fig. 7(b). In Fig. 7(b), I_{ph} is the photocurrent, R_S is the series resistance, L_S is the series inductance due to narrow electrode structure, R_D and C_D are the resistance and the capacitance in the depletion layer, respectively, R_{HJ} and C_{HJ} are the resistance and the capacitance at the heterobarrier, respectively, with suffix "1" and "2" meaning two heterobarriers, one is for electrons and the other is for holes, and R_L is the load resistance. The physical mechanism of the capacitance and the resistance at the heterobarrier, C_{HJ} and R_{HJ}, is as follows. The heterobarriers in the MSM-PD cause trapping of the photo-generated electrons and holes at conduction band discontinuity and valence band discontinuity, respectively, and negative and positive electronic charge are stored there. The charge storage is expressed by the capacitance C_{HJ}. The trapped elec-

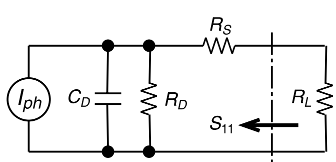


(a) For 4 V bias voltage.

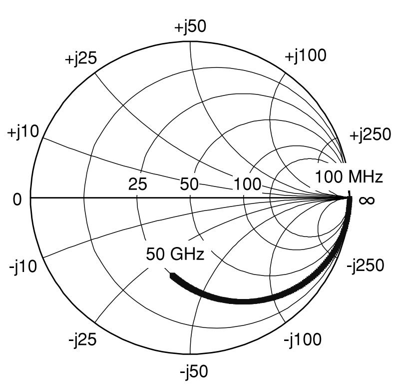


(b) For 10 V bias voltage.

Fig. 5 Measured S_{11} parameter of the MSM-PD for $W_E = W_S = 1\,\mu$m and the detection area of $10\,\mu$m $\times$ $10\,\mu$m.



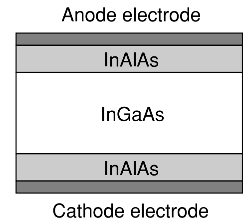
(a) Conventional simple equivalent circuit.



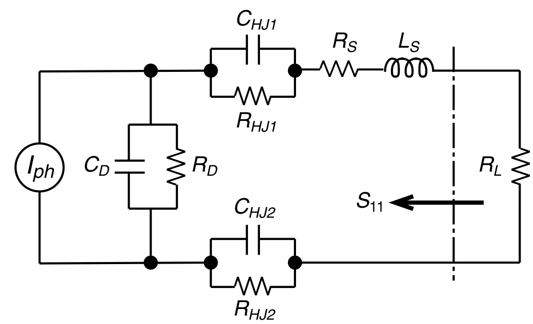
(b) Calculated S_{11} parameter.

Fig. 6 Conventional simple equivalent circuit for photodetectors and the calculated S_{11} parameter for C_D = 100 fF, R_D = 1 MΩ and R_S = 25 Ω.

trons and holes then overcome the heterobarrier due to thermionic emission and then drift toward the electrodes. The rate of the thermionic emission is expressed



(a) One-dimensional model.



(b) Equivalent circuit.

Fig. 7 One-dimensional model and the proposed equivalent circuit for the heterostructure MSM-PD.

Table 1 Extracted device parameters.

Notation	4 V bias	10 V bias
R_S	36.7 Ω	38.2 Ω
L_S	36 pH	44.5 pH
R_D	8040 Ω	11.5 kΩ
C_D	112 fF	58.1 fF
R_{HJ1}	198 Ω	90.4 Ω
C_{HJ1}	432 fF	313 fF
R_{HJ2}	150 Ω	0 Ω
C_{HJ2}	119 fF	0 fF

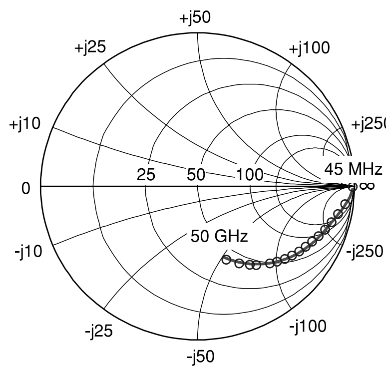
by the time constant of $C_{HJ} \times R_{HJ}$ in our equivalent circuit. From the equivalent circuit shown in Fig. 7(b), the input impedance Z_{in} and the S_{11} parameter are given as;

$$Z_{in} = R_S + j\omega L_S + \frac{R_D}{1 + j\omega C_D R_D} + \frac{R_{HJ1}}{1 + j\omega C_{HJ1} R_{HJ1}} + \frac{R_{HJ2}}{1 + j\omega C_{HJ2} R_{HJ2}} \quad (1)$$

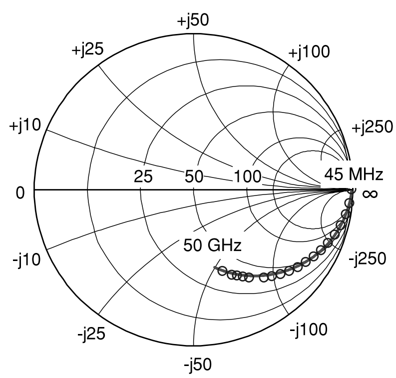
$$S_{11} = \frac{(Z_{in}/50) - 1}{(Z_{in}/50) + 1} \quad (2)$$

The measured S_{11} parameter is fitted with the above equations. In Fig. 8, circles are the measured S_{11} parameter, and solid lines are the fitting curve for 4 V and 10 V. The fitted curves agree well with the measured results. We can then extract the device parameters from the fitted curve, and the extracted values of parameters are shown in Table 1.

The series resistance is about 37 Ω, which is mainly attributed to the resistance of the narrow (1 μm) and thin (100 nm) interdigital electrodes. For +4 V bias voltage, two heterobarriers are extracted. However, for +10 V bias voltage, only one heterobarrier is extracted.



(a) For 4 V bias voltage.



(b) For 10 V bias voltage.

Fig. 8 Measured and fitted S_{11} parameter of the MSM-PD.

This means that electrons can overcome the heterobarrier because of high bias voltage and low effective mass of electrons, and only a heterobarrier for holes is extracted. It is also found that the time constants for the heterobarriers, $C_{HJ1} \times R_{HJ1}$ and $C_{HJ2} \times R_{HJ2}$, for +10 V bias are smaller than that for +4 V bias, indicating weak carrier trapping effect at the heterojunction due to an increased population of high energy electrons and holes by the high bias voltage.

5. Frequency Response

From the proposed equivalent circuit shown in Fig. 7(b), we can get the frequency response of the MSM-PD, and is given as;

$$\frac{V}{I_{ph}} = \frac{R_L}{R_L + Z_{in}} \frac{R_D}{1 + j\omega C_D R_D}. \quad (3)$$

Since the photocurrent is generated only in the InGaAs layer, the current source is connected parallel to R_D and C_D.

Figure 9 shows the frequency response of the MSM-PD for +4 V and +10 V bias voltage. In Fig. 9, squares and circles are the measured results and the dashed lines are calculated results from Eqs. (1) and (3) with $R_L = 50\,\Omega$. The difference between the measured and the calculated results is mainly due to the effect of carrier transit-time. We assume the frequency response of

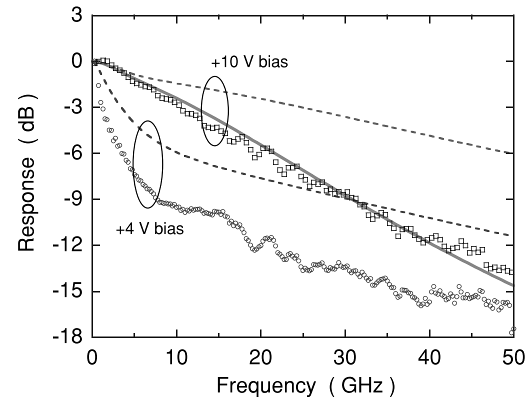


Fig. 9 Measured and calculated frequency response.

the carrier transit time, $H(f)$, to be

$$H(f) = \frac{1}{\sqrt{1 + (f/f_T)^2}} \quad (4)$$

$$f_T = \frac{2.4}{2\pi} \frac{v}{D} \quad (5)$$

where v is the carrier transit velocity and D is the carrier transit length, which is approximated as $D = [(T_U + T_A)^2 + W_S^2]^{1/2}$ with T_U and T_A being the thickness of the upper InAlAs layer and the thickness of the InGaAs layer, respectively. The frequency response taking account of $H(f)$ for $v = 7 \times 10^6$ cm/s is also shown with a solid line in Fig. 9 for +10 V bias voltage. The solid line agrees well with the measured result. For +4 V bias voltage, good agreement between the measured and the calculated frequency response cannot be obtained because the InGaAs layer is not fully depleted and the f_T cannot be expressed as a simple formula shown in Eq. (5) due to unsaturated carrier transit velocity for +4 V bias voltage.

6. Conclusion

We proposed an equivalent circuit model of InAlAs/InGaAs/InP heterostructure MSM-PDs to describe the measured S_{11} parameter. The measered S_{11} parameter deviates from equi-resistance lines due to carrier trapping effect at the heterojunction. We express the carrier trapping effect with the parallel combination of a resistance and a capacitance in our equivalent circuit. Then the measured S_{11} parameter was fitted with the calculated S_{11} parameter derived from the proposed equivalent circuit model, and the fitted S_{11} parameter agrees well with the measured S_{11} parameter. And we can successfully extract the device parameters from the fitted S_{11} parameter. For a low bias voltage, two heterojunctions are extracted, which are for electrons and holes, and for a high bias voltage, only one heterojunction is extracted. This means that electrons can overcome the heterobarrier because of high bias voltage and low effective mass of electrons, and only a heterobarrier for holes is extracted. It is also found that the time constants at the heterojunctions decreases for high bias condition, indicating weak carrier trapping effect at the heterojunction due to an increased population of high energy electrons and holes by the high bias voltage.

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