The Analysis and Design of High Power Millimeter Wave Pulse Detector for 2 mm Frequency Band

Guangqiang Wang[1], **Jianguo Wang**[2,3], **Xingzhou Wang**[2] **and Ruyu Fan**[1,2]

[1]Department of Engineering Physics, Tsinghua University, Beijing 100084, China
[2]Northwest Institute of Nuclear Technology, Xi'an 710024, China
[3]School of Electronics and Information Engineering, Xi'an Jiaotong University, Xi'an 710049, China

Abstract— The research progress of a high power millimeter wave pulse detector for 2 mm frequency band is presented here. This power detector, so-called resistive sensor, is composed of a 2 mm standard waveguide and a semiconductor sensing sample within it. At first, the principle of the detector is analyzed theoretically, and the sensitivity of the detector in the warm-electron region is derived. Then the structural parameters of the detector are calculated and optimized to make the frequency response flat over the waveguide frequency band. A three-dimensional finite difference time domain (FDTD) method is used here. The results show that, while the biased voltage on the detecting element is 10 V, the sensitivity of the optimized detector is about 6 V/kW with a fluctuation less than 27% in the frequency range 113–173 GHz, especially less than 9.8% in the frequency range 130–160 GHz. Compared with the diode detectors in 2 mm frequency band, the designed semiconductor detector shows better performance in pulse power measurement.

1. INTRODUCTION

Due to the potential applications in radar, communication and so on, the high power microwave (HPM) sources are developing toward millimeter wave region rapidly, and a lot of works in the generation of high power millimeter waves have been done in some laboratories all over the world [1]. For example, our research team successfully designed [2] and tested Q-band high power relativistic surface wave oscillator in recent years. Along with the developments of the sources, the power measurement techniques should be improved to be used for HPM pulses with higher frequency.

In general, the main method to measure the peak power of HPM pulses is to use the calibrated diode detectors or semiconductor detectors, namely resistive sensors. As the diodes have small breakdown voltages, the HPM pulses should be strongly attenuated, which leads to the decrease of the measurement accuracy. But the semiconductor detector , composed of a standard waveguide and a semiconductor sensing sample, can convert the pulse power as high as kW to a DC voltage pulse directly without any attenuation based on the hot-carrier effect in semiconductor under high electric field [3]. Power measurements of nanosecond pulses using it have highlighted its advantages in centimeter wave region [4, 5]. Also it is anticipated to have good performance for the lack of accurate attenuators in millimeter wave region, which has been proved in the frequency band as high as W-band until now [6].

In this paper, the research progress of a high power millimeter wave pulse detector for 2 mm frequency band in our laboratory is presented. Though the window size of the detector is very small ($1.651 \times 0.8255\,\mathrm{mm}^2$), the new structure of the sensing sample and the development of the microfabrication technology make its fabrication possible. This detector will be used in the pulse power measurements of our Q-band source.

2. PRINCIPLE OF THE DETECTOR

2.1. Hot-carrier Effect in Semiconductor [7]

When the electric field applied to the semiconductor is not very high, the current density J of the semiconductor is proportion to the magnitude of the electric field $|E|$, e.g., $J = \sigma|E|$. However, as the electric field increases up to about 10^3 V/cm, the deviation of the proportion relation is found in experiments. Lots of studies indicated that the change of mobilities of carriers in semiconductor under high electric field, which was called hot-carriers, was the reason of the deviation. The energy that carriers gained from electric field is so much that the average energy of carriers is higher than in thermal equilibrium, so is the effective temperature T of the carriers. Thus, the mobilities of the carriers decrease, while the resistance of semiconductor increases. This is the hot-carrier effect in semiconductor under high electric field.

Taking n-type silicon (n-Si) as an example and considering the scattering between the electrons and crystal lattices, the proportion between the effective temperature of electrons with and without applied electric field is gained:

$$\frac{T_e}{T_0} = \frac{1}{2}\left[1 + \sqrt{1 + \frac{3\pi}{8}\left(\frac{\mu_0 |E|}{u}\right)^2}\right] = \alpha^2 \tag{1}$$

where T_e and T_0 are the effective temperature of electrons with and without applied electric field, respectively, u is the velocity of the phonon, and μ_0 is the mobility of unheated electron. If $\mu_0|E| \ll u$, the expression (1) can be expanded in power series, and ignores the quadratic term and terms with higher order, yielding that:

$$\alpha \approx 1 + \frac{3\pi}{64}\left(\frac{\mu_0 |E|}{u}\right)^2 \tag{2}$$

Obviously, the effective temperature of electrons always rises, though unconspicuous, even if the applied electric field is very small. Usually the electrons are called warm-electrons when the applied electric field coincides with this assumption.

2.2. Prototype and Sensitivity of the power detector

The typical structure of the power detector in millimeter wave region [6] is given in Figure 1. It is composed of a standard waveguide, a semiconductor sensing sample within it and a DC bias current source to supply a bias voltage U_0 on the sample. Propagating through the waveguide, the electric field of the HPM pulse is applied to the semiconductor sample by stimulating the TE_{10} mode, whose electric field is in the vertical direction. Due to the high electric field, the carriers of the sample are heated. As the effective temperature of the carriers rises, the resistance of the sample increases. Simultaneously, the bias voltage on the sample increases in a shape the same as the pulse measured, and this is the output voltage U_s of the detector. With carefully calibrated in the waveguide frequency band, the pulse power of the HPM pulse is determined.

Figure 2 shows the sketch map of the cross-section of the sensing sample, indicating some structural parameters of the semiconductor. Two same semiconductors with length of l are separated with a small distance (μm), and shorted with thin copper foil. The lower contact of one of the semiconductors is grounded with the waveguide while the other is isolated. Thus the two semiconductors and upper thin copper foil compose a DC circuit with a bias current source. The feeding and output of the voltage dropped on the sample are easily achieved through the small obstacle.

According to the circuit analysis, the output voltage in respect to HPM pulse can be written as

$$\frac{U_s}{U_0} = \frac{\Delta R}{R_0} = \sqrt{\frac{T_e}{T_0}} - 1 = \alpha - 1 \tag{3}$$

where R_0 is the initial resistance of the sensing sample. Substituting (1) to (3) and normalizing the average electric field $\langle E \rangle$ in vertical direction in the sensing sample to the maximum electric

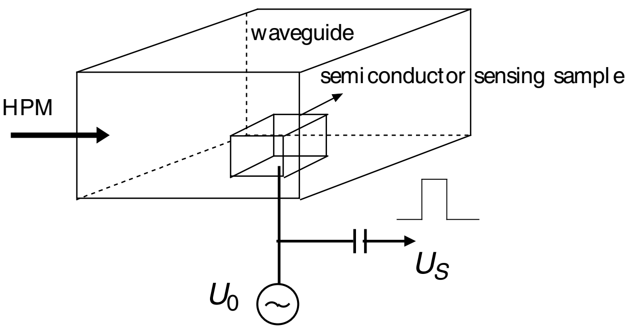

Figure 1: Sketch of semiconductor power detector.

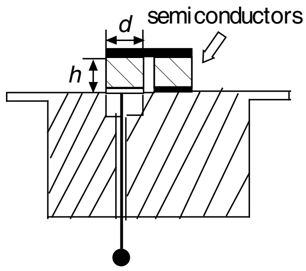

Figure 2: Cross-section of the sensing sample.

field E_0 in the centre of empty waveguide, one can obtain the relationship between the U_s and the pulse power P_{in} as followed:

$$\left(\frac{U_s}{U_0}\right)^4 + 4\left(\frac{U_s}{U_0}\right)^3 + 5\left(\frac{U_s}{U_0}\right)^2 + 2\left(\frac{U_s}{U_0}\right) = \frac{45\pi^2(\frac{\mu_0}{u})^2\langle\frac{E}{E_0}\rangle^2}{ab\sqrt{1-(f_c/f)^2}}P_{in} \tag{4}$$

where a and b are the length of the long and short side of the waveguide, respectively, f is the frequency of the HPM pulse, and f_c is the cut-off frequency of the waveguide. Defining the relative sensitivity of the detector as $\xi = U_s/(U_0 \cdot P_{in})$, one can get ξ by solving the Equation (4). In the warm-electron region, the relative sensitivity is derived from Equation (2) and (3); that is,

$$\xi = \frac{45\pi^2(\frac{\mu_0}{u})^2\langle\frac{E}{E_0}\rangle^2}{2ab\sqrt{1-(f_c/f)^2}} \tag{5}$$

A proportion relation is found between the relative sensitivity and the pulse power under linear approximation. Denoting warm-electron coefficient in AC electric field as $\beta = \frac{3\pi}{64}(\frac{\mu_0}{u(f)})^2$, and according to the paper [4], the expression (5) is rewritten, yielding that:

$$\xi(f) = \frac{480\pi}{ab\sqrt{1-(f_c/f)^2}}\beta_{dc}\left[1/2 + 1/\left[1+(2\pi f\tau_\varepsilon)^2\right]\right]\left\langle\frac{E^2}{E_0^2}\right\rangle \tag{6}$$

where β_{dc} is the warm-electron coefficient in DC electric field, τ_ε is the phenomenological energy relaxation time.

3. DESIGN AND OPTIMIZATION OF THE PARAMETERS OF THE DETECTOR

3.1. Calculation Method

The pulse power detector for 2 mm frequency band is designed to be made up of a WR7 standard waveguide, whose window size is $1.651 \times 0.8225\,\text{mm}^2$, and a sensing sample including two same n-Si plates and a thin copper foil. It's suitable to be used in the frequency band of 113 GHz–173 GHz. The material of n-Si is chosen for its high time response and easily fabrication.

In expression (6) there is a dependence of the relative sensitivity on the frequency of the pulse measured in the linear region of the detector. To reduce the work of the calibration and increase the accuracy of the detector, this dependence should be avoided, that is, the parameters of the detector would be optimized to make the frequency response flat enough. Because of the disperse in the waveguide and the dependence of the warm-electron coefficient on the frequency, the relative sensitivity would decline. So the characteristic dimensions and the specific resistance ρ of the sample should be varied to make the average electric field in the sample increase to compensate it. Meanwhile, these parameters are restricted by that the voltage standing wave ratio (VSWR) is no more than 1.3.

A three-dimensional finite difference time domain (FDTD) method is used here to calculate the electric field in sensing sample. The simulated model is illustrated in Figure 3, where the length of the waveguide is 5 mm. An excitation of sinusoidal wave of TE_{10} mode is adopted all over the frequency band. There are two absorbing boundary conditions mathematically specified in both begin and end of the model. The sample is treated as a whole obstacle, and the thickness of the copper foil is neglected.

3.2. Results of the Optimization

Preliminary calculations are firstly performed to get moderate VSWR. Between the plane where microwave excited and the sample, a part standing wave is clearly seen in the distribution of electric field in y direction. When the transverse dimensions of sensing sample are $0.1 \times 0.2\,\text{mm}^2$ and the specific resistance is $\rho = 2\,\Omega\cdot\text{cm}$, the VSWR of the detector is about 1–1.25 in the waveguide frequency band. The length of the sample doesn't take much effect in VSWR, but in the average electric field in the sample.

Results of followed simulations are shown in Figure 4. The thick line is corresponding to ideal curve of $\frac{\langle E^2(f)/E_0^2(f)\rangle}{\langle E^2(f_l)/E_0^2(f_l)\rangle}$, which is calculated from expression (6) to make the relative sensitivity unchanged, and other curves are in respect to different length. Here f_l is 113 GHz, the lowest frequency in the waveguide frequency band. According to the analysis in 3.1, the optimized length is that the curve coincides with the thick line or the two have the same varying trend. Evidently $l = 0.75$ mm is the best choice, as both sides of its curve have contrary variation. Further computation of relative sensitivity in length of 0.75 mm is plotted in Figure 5. The sensitivity of 0.6 kW^{-1} is obtained with a fluctuation less than 27% in the frequency range 113–173 GHz, especially less than 9.8% in the frequency range 130–160 GHz, which means the frequency response is rather flat. Ultimately, all the parameters of the power detector are optimized and determined as follows: $a = 1.651$ mm, $b = 0.8225$ mm, $h = 0.1$ mm, $d = 0.1$ mm, $l = 0.75$ mm, and $\rho = 2\,\Omega\cdot$cm.

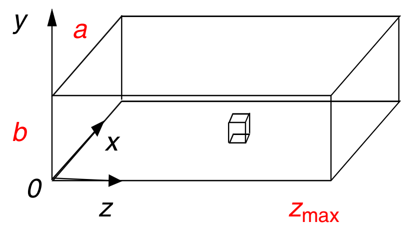

Figure 3: The calculation model of the detector.

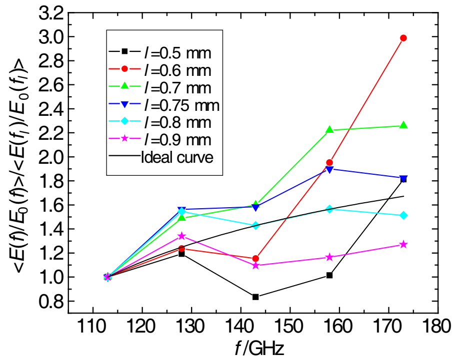

Figure 4: The dependence of the electric field on frequency.

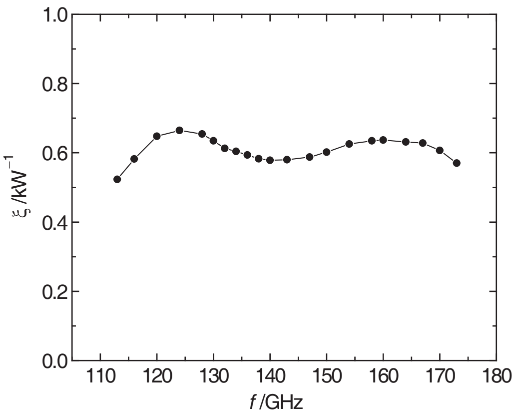

Figure 5: The relative sensitivity of detector with.

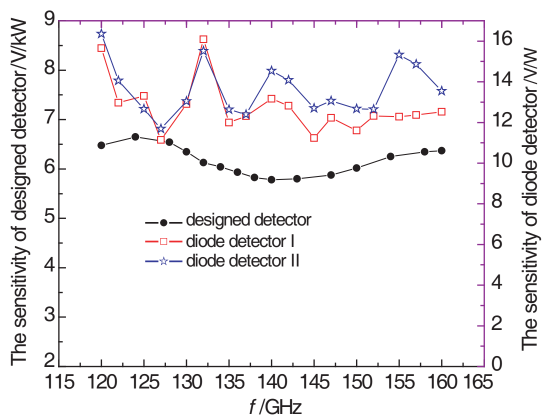

Figure 6: The sensitivities of designed detector the length of 0.75 mm of the sample and diode detectors.

4. CONCLUSION

Based on hot-electron effect in n-Si, a pulse power detector for 2 mm frequency band is analyzed theoretically and designed. Parameters of the detector are optimized to keep the relative sensitivity in warm-electron region flat with three-dimensional FDTD method. Compared with the purchased diode detectors in 2 mm frequency band, the advantages of our detector is obviously seen in Figure 6, where the designed detector is biased with a DC voltage of 10 V. Diodes have much higher sensitivities of about 13 V/W, fluctuating in a level of about 45.6% in the frequency range of 120 GHz–160 GHz. So the designed semiconductor detector has more flatter frequency response, and can measure pulse power with a magnitude of kW directly with an output signal of the order of a few tens of volts, which leads to less attenuation used in the high power measurements and good performances in high electromagnetic interference environments. The detector is seeking for fabrication, and will be used in the experiments of our Q-band HPM source if possible.

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