Resistive Sensor for High Power Microwave Pulse Measurement

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ABSTRACT

In this paper, the review of a resistive sensor (RS) that has found application for high power microwave pulse (HPM) measurement is presented. The performance of the RS is based on the electron heating effect in semiconductor. In general, the RS has demonstrated advantages over a conventional diode that is also used to measure HPM pulses. The RS can measure HPM pulses directly; it is resistant to large power overloads and demonstrates very good long-term stability. The RS can produce an output signal of the order of a few tens of Volts without any amplification circuit and it can be done sufficiently fast to measure nanosecond duration HPM pulses. In this paper, different types of the RS developed, manufactured and tested in our laboratory are presented. They are: the cross-waveguide RS for the intermediate pulse power level, the waveguide type RS with diaphragm for the nanosecond duration HPM pulse measurement, the coaxial type RS for the measurement of the microwave pulses in a wide frequency range and the RS for the measurement high power pulses in a millimetre wave range. The RS for the measurement of HPM pulses in the circular waveguide is also considered.

1.0 INTODUCTION

At present, different types of pulsed high power microwave (HPM) oscillators and amplifiers are being intensively studied in laboratories as well as being manufactured by industry. On the one hand, since the HPM sources are increasingly used in communication systems, radars, electromagnetic test facilities, scientific research, and military projects the potential threat from them on the electronic equipment should be taken into account. On the other hand, intentional attacks on the electronic infrastructure using HPM sources might be expected and possible disturbances with fatal consequences for civil and military systems should be considered. To perform measurements of HPM pulses the reliable sensors are necessary. Traditionally, calibrated diodes are used to measure the power of microwave pulses, but they can handle only a very low power level, therefore the HPM pulse being measured has to be strongly attenuated. An additional attenuation results in the decrease of the measurement accuracy. Moreover, the problems may arise when measuring small DC signal from the diode due to the presence of stray pickup and electromagnetic interference, which are typical to the environment of HPM sources. Novel electro optic measurement techniques [1] can be applied efficiently in HPM environment, but use of external sensitive equipment (such as lasers, polarizers, other optics) also restricts the application areas.

An alternative HPM pulse measurement device – resistive sensor (RS) [2] helps to overcome these difficulties. The performance of the RS is based on electron heating effect in semiconductors. The sensing element (SE) of the RS is placed in the transmission line. Electric field of the HPM pulse heats electrons in the SE, its resistance increases and by measuring this resistance change, the HPM pulse power is determined. Such compact and rigid sensor can measure HPM pulses directly, produces high output signal, is overload resistant, and demonstrates very good long-term stability. In this paper, different types of the RS are presented. The paper is organized as follows. In the second section the principle of the performance of the RS and its sensitivity are described. The actual design of the RS for the rectangular waveguide is presented in the third section. Coaxial RS is described in the fourth section. The RS for the circular waveguide is considered in the fifth section.

2.0 THE RESISTIVE SENSOR

The investigation of semiconductors subjected to a strong electric field began more that fifty years ago when it was found [3] that for large electric fields the current deviates from the dependence predicted by Ohm's law. It was understand that in the strong electric field, electrons gain additional energy from the electric field and a new steady state is established with mean electron energy greater than equilibrium one. As a rule, heated electrons are more frequently scattered by lattice imperfections (phonons), and the resistance of the semiconductor usually increases. It was realised that the resistance change in the strong electric field could be used for pulsed microwave signal measurement. By placing semiconductor sample in the transmission line and measuring the resistance change occurring when the electric field of the microwave pulse heats electrons in the sample, the microwave pulse power in the transmission line can be determined.

2.1 Sensing Element and Output Signal

Since the resistance change of the semiconductor is put as a basis for resistive sensor's operation, for HPM pulse measurement we actually use a resistor made from n-type Si. The SE is bar or plate-shaped piece of Si with ohmic contacts. Impurity diffusion followed by metal evaporation is used to form contacts. A typical sample length is from 0.1 to 10 mm. Depending on the particular application, various ingots of silicon with different specific resistances are used.

To measure the resistance change in the microwave electric field, the SE should be connected to a DC circuit. Therefore, the output signal from the RS being measured using a high input resistance measuring unit can be expressed in the following way

$$U_S = U_0 \frac{\Delta R}{R}, \tag{1}$$

where U_0 is the DC voltage drop on the SE and $\Delta R/R$ is a relative resistance change of the SE, obtained by averaging the instantaneous current over the period of the microwave electric field. In a low power limit the strength of an average microwave electric field in the SE is sufficiently small. Therefore, its resistance change can be expanded in a power series of the electric field and only first non-vanishing term can be taken into account, thus yielding [2]

$$\frac{\Delta R}{R} = \beta^*(f)\langle E\rangle^2, \tag{2}$$

where $\beta^*(f)$ is frequency dependent, so-called, an effective warm-electron coefficient defining a deviation of the current-voltage characteristic from Ohm's law and $\langle E\rangle$ is an average amplitude of electric field in the SE. The region where (2) expression is valid is called a warm-electron region. In general, the effective warm electron coefficient is frequency dependent and this dependence accounts for the influence of electron-heating inertia on the resistance change in the microwave electric field:

$$\frac{\beta^*(f)}{\beta_0^*} = \frac{1}{3}\left[1 + \frac{2}{1+(2\pi f \tau_\varepsilon)^2}\right], \tag{3}$$

where β_0^* is a value of the effective warm-electron coefficient in a low frequency region and τ_ε is a phenomenological energy relaxation time. Typical values of β_0^* and τ_ε for n-Si at a room temperature are collected in Table 1. From (3) one can found that at 12 GHz the decrease of β^* due to heating inertia is roughly 3%. Therefore, the influence of heating inertia on β^*can be neglected up to and including X-band.

Experimental investigations have revealed that the warm-electron approximation holds well up to the electric field strength around 1 kV/cm, at which $\Delta R/R$ is of the order of 10%. At a higher electric field, there is a considerable deviation of the relative resistance change from the dependence predicted by expression (2). It was found that over a wider range of the electric field strength, the resistance change is described by the following empirical relation, with two adjustable parameters

$$\frac{\Delta R}{R} = \frac{\sqrt{1 + 4k_n^* \beta^* \langle E \rangle^2} - 1}{2k_n^*}, \tag{4}$$

where k_n^* describes the deviation of $\Delta R/R$ from quadratic dependence predicted by (2). Typical values of k_n^* for n-type Si at room temperature are presented in Table 1.

Table 1: Typical values of phenomenological parameters characterising current voltage characteristic of n-Si at a room temperature for different specific resistance ρ material

ρ, Ω·cm	β_0^*, cm^2/V^2	k_n^*	τ_ε, s
5	9.0×10^{-8}	3.0	2.9×10^{-12}
20	9.3×10^{-8}	3.4	
200	10.1×10^{-8}	4.3	

2.2 Sensitivity

Let us consider a sensitivity of the RS in the linear region where the output signal of the RS is proportional to the pulse power P propagating in the transmission line. Since the resistance change of the SE is the quantity indicating pulse power level, it is convenient to define the sensitivity ζ of the RS as

$$\zeta = \frac{\Delta R / R}{P}, \tag{5}$$

Definition (5) is not unique. Often sensitivity is defined as a signal to power ratio. Taking into account that the signal amplitude depends not only on the DC voltage drop on the SE but on the input resistance of the measurement unit used for the output signal measurement, the proposed definition of the sensitivity is likely more acceptable. Inserting (2) and (3) into (5) one can get the following expression

$$\zeta = \frac{\beta_0^*}{3}\left[1 + \frac{2}{1 + (2\pi f \tau_\varepsilon)^2}\right]\frac{\langle E \rangle^2}{P}, \tag{6}$$

describing the sensitivity of the RS in the linear region. The average electric field is the only unknown quantity in (6). Thus determining it, the sensitivity of the RS in the linear region can be calculated. For the calculation of the average electric field in the SE and optimisation of the frequency response of the RS, we used finite-different time-domain (FDTD) method [4]. When $\langle E \rangle$ in the SE is determined, the dependence of $\Delta R/R$ on P can be calculated in a wider dynamical range of the power transmitted through the transmission line using (4).

2.3 DC Pulse Supply

Considering expression (1), one can see that the output signal linearly grows with DC voltage drop on the SE. The increase of the DC voltage applied to the SE is limited by sensor heating that worsens sensor's characteristics. Instead, we used a pulsed current source [2]. It produces roughly 120 μs DC current pulse. The amplitude of the current is adjusted to get desirable voltage drop on the sensing elements. After 100 μs when the current pulse starts, the HPM pulse source is triggered. Therefore, the output signal appears as a short video pulse on the pad of the feeding pulse. A differencing circuit cuts the pad and the useful signal is measured by an oscilloscope. The pulsed current source allows a significant increase of the output signal from the RS without any amplification circuit.

3.0 THE RS IN RECTANGULAR WAVEGUIDE

Rectangular waveguides are widely used as a transmission line for HPM applications. Therefore, we have focused our attention on the measurement of pulsed power in the rectangular waveguides.

3.1 Cross-waveguide Type RS

A cross waveguide type RS is made as a section of standard waveguide where the sensing element is mounted. A schematic view of the RS is shown in Figure 1a. The sensing element of the RS is placed in the centre of the waveguide. It is a bar-shaped piece of semiconductor with Ohmic contacts on its ends. The specific resistance of the semiconductor used as the sensing element is in the range 20-200 Ω-cm. The length of the sensing element corresponds to the dimension of the narrow wall of the waveguide. The grounded end of the SE is directly connected to the waveguide. The other end of the sensing element is isolated and connected to the measurement circuit and current source. The RS described above has been mainly used for the measurement of intermediate levels of pulse power (~1 kW) at X-band (waveguide size 23x10 mm^2).

Considering the thermal characteristics of the cross waveguide type RS, it was shown that some average heating of the sensing element occurs when it is fed by a sequence of microwave pulses. Electron and lattice heating inertia differ by many orders. Therefore, two kinds of measurements can be performed independently: the measurement of the pulse signal that appears due to electron heating and the measurement of the increase of average resistance caused by the average heating of the sensing element. The measured pulse signal is proportional to the pulse power, while the increase of resistance is proportional to the average power absorbed in the sensing element. This means that the cross waveguide sensor can serve as a pulse power meter and bolometer simultaneously. Making use of this feature, the RS can be independently calibrated, replacing the microwave electric field in the sensor by a DC electric field the strength of which can be measured with high accuracy.

The readings of two sensors calibrated in such a way have been compared with the readings of Russian (former Soviet Union) pulse power standard. The measurements have been performed for 18 years since 1982 [2]. During this long-term experiment, some change of the sensitivity within ± 4 % was detected. Having in mind that the main error of the standard was ± 4 % it becomes clear that the tested sensors demonstrate very good long-term stability.

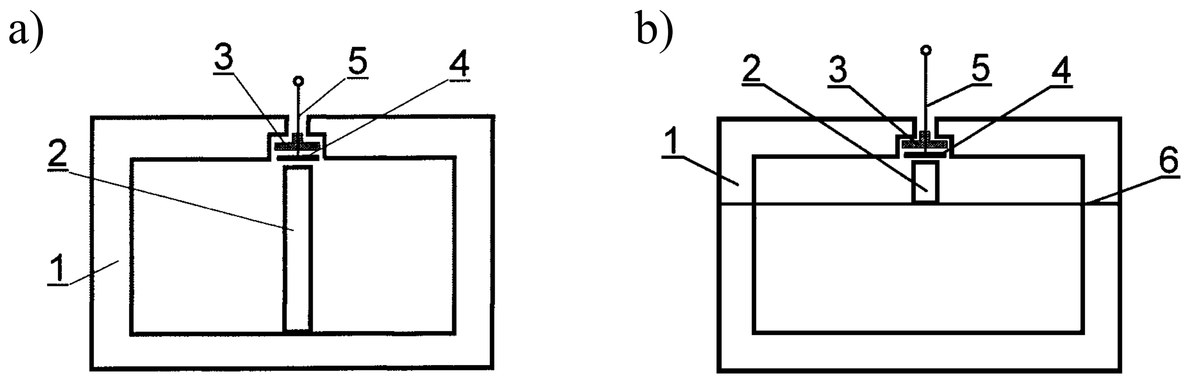

Figure 1: Schematic views of cross- waveguide type RS (a) and diaphragm type RS (b). 1 – waveguide, 2 – SE, 3, 4 – insulating and metallic washers, 5 – output, 6 – diaphragm

3.2 Diaphragm Type RS

Improving thermal characteristics of the sensor and widening its possible applications for HPM pulse measurements, the diaphragm type RS shown in Figure 1b has been developed. It is seen that in this case the sensing element is placed in the centre of the waveguide between a thin metal foil and a wide wall of the waveguide. The length of the SE roughly corresponds to 1/10 of the waveguide's narrow wall.

At least two advantages of the diaphragm type RS over the cross-waveguide type can be mentioned. On the one hand, by decreasing the length, thermal characteristics of the SE are improved. On the other hand, since the sensing element occupies only a part of the waveguide window, a smaller reflection from it can be expected even though a lower specific resistance semiconductor is used for the manufacturing of the sensing element.

Diaphragm type RS have been manufactured and tested beginning from L up to Ka-band. They are used in Russian, Sweden, USA and other countries laboratories dealing with HPM pulses. The RS found application for the measurement of HPM pulse power density in free space. The RS connected to a horn antenna from one side and to a matched load from the other comprise a unit that is able to measure pulse power density up to a few MW/m^2 [5]. The measurements were carried out in anechoic chamber at SAAB Military Aircraft, Sweden.

The diaphragm type RS has been upgraded for the measurement of nanosecond-duration HPM pulses. The RS from the S to Ka-band has been manufactured, calibrated and tested. The output signal dependencies on pulse power are shown in Figure 2a. It is seen that using DC pulse feeding output signals up to 30 V are obtained. It should be pointed out that the RS has been calibrated up to pulse power levels available in the laboratory. They can likely be used at higher pulse power levels, ultimately limited by air breakdown in the waveguide. Investigations of the time response of the manufactured RS have revealed that manufactured RS can measure microwave pulses with duration on the order of a few tens periods of microwave oscillations. It was confirmed by tests of the X-band RS using short HPM pulses generated by a SINUS-6 electron beam accelerator driving backward wave oscillator at the University of New Mexico [6].

The main drawback of the waveguide type RS for short HPM pulse measurement is a large variation of the sensitivity (5) in a waveguide's frequency band. It was determined that the sensitivity of the X-band RS changes in the frequency band by more than a factor of two. The same frequency response is likely to be characteristic of the RS in other frequency bands as well. Having in mind the drawback of the waveguide type RS, we performed investigations of factors influencing frequency response.

Making use of a FDTD method, peculiarities of the interaction of the semiconductor sample inserted under thin metal diaphragm in the waveguide have been investigated. It was shown that the average electric field strength in the SE is influenced by resonance phenomena [7]. Resonance occurs when the effective length of the diaphragm for wave propagating under it becomes a whole number of half-wave. Varying electrophysical parameters of the diaphragm type RS (diaphragm length, dimensions and specific resistance of the SE) and taking into account that the resistance of the RS should be less or equal 50 Ω the optimal set of parameters providing the smallest possible sensitivity variation in the waveguide's frequency band has been determined. Maximum to minimum sensitivity ratio 1.09 was found for the optimal set of parameters.

Theoretical predictions have been proved experimentally. Experimentally measured frequency responses of the initial and optimized RS are shown in Figure 2b. It is seen, that the optimized RS is characterized by a smooth dependence of the sensitivity on frequency. Experimentally measured sensitivity variation in waveguide's frequency range is roughly ±6%. That is sufficiently close to the theoretically predicted value 1.09. The absolute value of measured sensitivity coincides well with calculated one. A small difference between the measured and calculated values can be attributed to size tolerances between the actual device and modelled prototype, to small mechanical displacement when installing the SE under the diaphragm, and to the measurement errors.

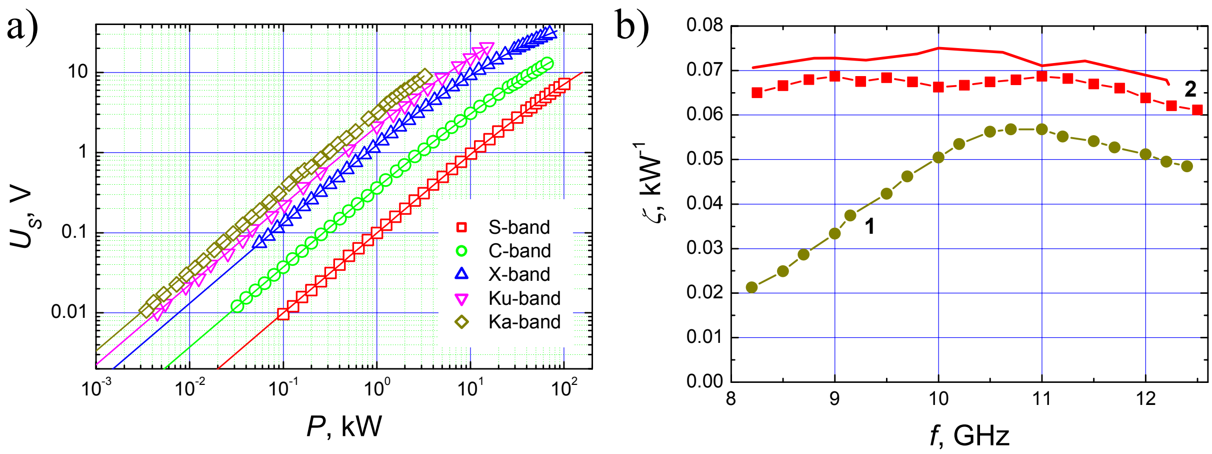

Figure 2: Output signal dependencies on microwave power (a) for the RS designed for short HPM pulse measurement at different frequency bands: points denote experimentally measured values using DC pulse supply producing 50 V DC voltage drop on the SE. Dependence of the sensitivity on frequency (b) for the initial (1) and optimized (2) X-band diaphragm-type RS: points show measurement results, solid line – theoretical prediction

3.3 RS for Millimetre Wave

High power microwave pulse generation techniques progressed rapidly towards higher frequencies in recent years [8]. This imposes new requirements for sensors that can be used for the measurement of HPM pulses in millimetre wave region. One of the possible solutions might be the RS. Unfortunately, the most successful concept of the diaphragm type RS could not be directly downscaled to the millimetre wave region due to the small dimensions of the waveguide. For the measurement of high power millimetre wave pulses in the frequency range 78-118 GHz (W-band, waveguide window 2.4×1.2 mm^2), we propose a new concept of the SE consisting of two separate samples mounted in the centre of the wide wall of the waveguide in a close proximity to each other [9]. Their upper contacts are shorted with a metal foil. The lower contact of one of the sensor is grounded while the other one is isolated. It is used for the RS feeding and the output signal measurement. To measure pulse power the RS is connected into a DC circuit with a current source. Thus, sensing elements are connected in series in respect to the DC circuit but in parallel in respect to the millimetre wave electric field.

We have performed FDTD simulations in order to investigate the interaction of such semiconductor structure with millimetre waves. It was found that some resonances occur in the SE when increasing its length in a wave propagation direction. Making use of the interplay between half wavelength resonance in the structure and the conductivity current in it, the increase of the average electric field in the sensor with frequency has been compensated by the electric field decrease in the waveguide due to waveguide dispersion and decrease of the electron heating effect with frequency (3). Thus, the RS having nearly independent sensitivity with frequency in a waveguide's frequency band has been proposed [9].

The RS with optimal dimensions of the SE (height $h = 0.1$ mm, width $d = 0.15$ mm, length in the wave propagation direction $l = 0.6$ mm) was manufactured. The main difficulty that we met with in manufacturing the sensing elements was dividing 0.1 mm thickness n-type Si wafer into individual dies. Using the mechanical cutting machine with a diamond wire or disc saw leads to the undesirable damage of the edges of the sensing element and large scattering of its initial resistance. Instead, we introduced the scribing and breaking of a semiconductor wafer into individual dies technology. The surface mounted device technology of component soldering was applied to fix sensing elements on polished metal disks those in turn were mounted into waveguide holders. Thus, finally the RS was manufactured as a section of W-band waveguide with the sensing elements inside. Two groups of the sensing elements with optimal dimensions were made from different specific resistance n-Si wafers, namely: the first group $\rho = 1$ Ωcm, the second – 2 Ωcm with a nominal DC resistance 11 Ω and 22 Ω, respectively. For final tests, three sensors from each group have been chosen.

The sensitivity, voltage standing wave ratio (VSWR), and insertion loss dependences on frequency have been measured using low power tunable millimetre wave source, reference wattmeter and lock-in amplifier. It was found that VSWR is less than 1.25 and insertion loss – 0.8 dB for the RS of both groups in a frequency range 78-118 GHz. Results of the measurements of the dependence of the sensitivity on frequency are presented in Figure 3a. It is seen, that the sensors of the second group are more sensitive than of the first. Such behaviour has been predicted by our theoretical considerations [9]. Taking into account finite thickness of the metal foil shorting upper contacts and an air gap between sensing elements reasonable agreement between measured and calculated values of the sensitivity was obtained. Details of the comparison can be found in [10]. From experimental results it is seen, that the measured sensitivity variation within waveguide frequency range was ±15% for the first group and ±8% for the second one. It is a very good result since available on a market the Agilent sensor W8486A devoted for the average power measurement demonstrates ±15% sensitivity variation in a 3 mm wave band.

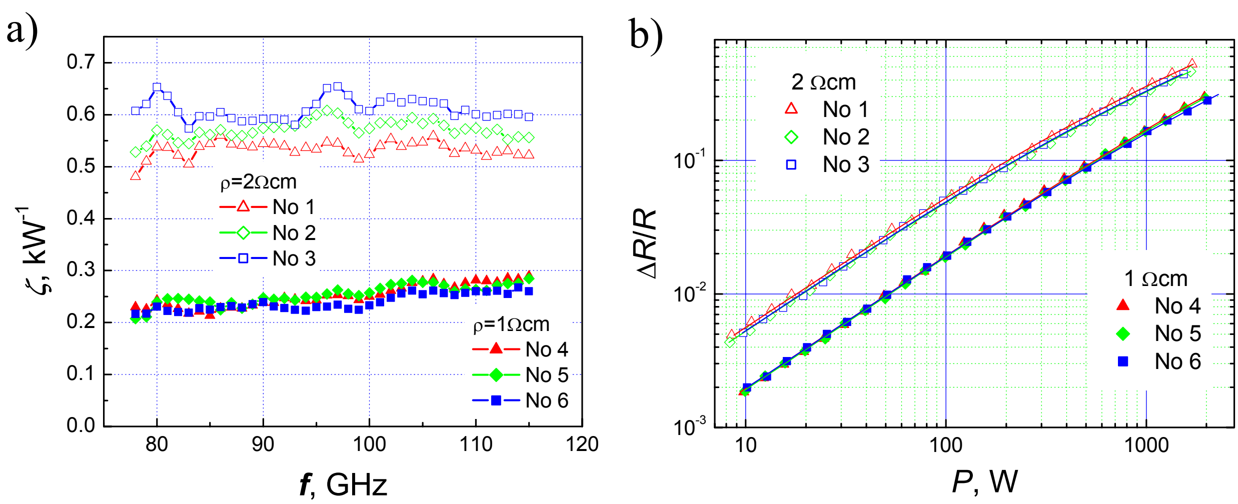

Figure 3: Experimentally measured dependence of the sensitivity on frequency (a) and dependence of the relative resistance change on pulse power in the waveguide (b) for both groups of sensors for millimetre wave

The dependences of the output signal on the pulse power were measured up to 2 kW using a magnetron operating at 94 GHz. The duration of millimetre wave pulses was 300 ns. In order to get high output signal, the RS was fed by a pulsed current source producing 10 V voltage drop on the sensing elements. At a maximum pulse power, the output signal was roughly 1.5 V for the RS of the first group and it exceeds 2 V for the second group. From the experimental data the dependence of the relative resistance change of the RS on the pulse power was determined. These results are shown in Figure 3b. It is seen that at a maximum pulse power the largest value of $\Delta R/R$ was about 20% for the first group of the RS and 50% for the second one. Having in mind that at a lower frequency the RS was successfully employed up to a twofold increase of the resistance, one can expect that the present RS could register even higher pulses of the millimetre waves.

4.0 COAXIAL TYPE RS

The application of the waveguide type RS is restricted by the bandwidth of the certain waveguide. Hence for the HPM pulse measurement in a wide frequency range a set of sensors has to be used. Therefore the measurement system becomes complicated and its cost increases. Moreover, at a lower frequency a size and weight of the waveguide section with the RS increases and it becomes inconvenient in use. These reasons pushed us to develop a coaxial type RS (CRS) that can be used in a wider frequency range.

The CRS was designed as a two terminal device. One of them will be used to connect the sensor to a coaxial line where the measuring microwave pulse is propagating. The other one is devoted to connect the CRS to the measuring circuit and sensor-feeding unit. The CRS was designed on a basis of 50 Ω impedance coaxial line. It actually consists of the SE and low pass filter. One contact of the SE is directly connected to the coaxial line's conductor, while the other one – to the coaxial line's shielding. Therefore the SE serves as a matched load and a pulse power detector simultaneously. To achieve good matching of the CRS with the coaxial line the resistance of the SE is set to be 50 Ohms. Since the dimensions of the sensing element are chosen much less than the wavelength of the microwave, the SE might be considered as a lumped element of the circuit. This is the reason why a good matching might be achieved in a wide frequency range. The main purpose of the low-pass filter of the CRS is to prevent the direct propagation of the microwave pulse to the measuring unit. At the same time the low-pass filter should not spoil the matching of the SE with the coaxial line in a wide frequency band. And finally, parameters of the low-pass filter influences on the response time of the CRS. Therefore all three factors should be taken into account when choosing parameters of the low pass filter.

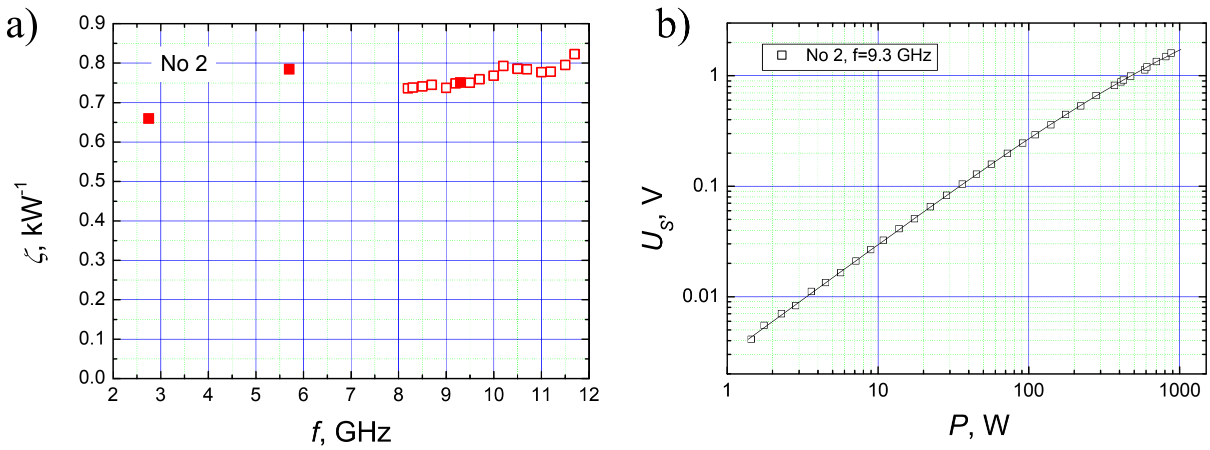

Figure 4: The dependence of the sensitivity on frequency (a) measured using magnetron generators (solid points) and X-band TWT (open points). The dependence of the output signal on pulse power at *f* = 9.3 GHz, U_0 = 4 V (b) for the coaxial RS with hybrid filter

As a low pass filter, we employed five elements Butterworth filter. Filters made from lumped elements, from the sections of a microstrip line and a hybrid filter were tested. In the hybrid filter the first element of the filter – the inductance – was partly replaced by a conductor coated by the layer of ferrite. It improves significantly the performance of the filter in high frequency region providing measurements of the microwave pulses in the frequency range 2-12 GHz. Frequency response of the CRS with hybrid filter is shown in Figure 4a. Solid points in the figure shows results obtained at fixed frequencies using magnetron generators open points demonstrate results measured using X-band TWT. It is seen, that sensitivity is slightly growing with frequency and from 2.7 GHz up to 11.7 GHz it increases by a factor 1.25. Measured VSWR was less than 1.6 within considered frequency range.

The output signal dependence of the CRS on a pulse power measured at frequency 9.3 GHz up to 1 kW is shown in Figure 4b. A DC current source producing 4 V voltage drop on the SE was used. It is seen that at a maximum pulse power the output signal more than 1.5 V is obtained.

4.0 RS FOR CIRCULAR WAVEGUIDE

In experiments with relativistic electron beams used for HPM pulse generation, a periodic rippled-wall circular waveguide is sometimes employed as a slow wave structure [11]. When the electron velocity becomes greater than the phase velocity of electromagnetic waves in the slow wave structure, the electron beam amplifies an injected electromagnetic wave producing HPM pulses in the output. Our recent activities has been concentrated on the elucidation of peculiarities of the interaction of the electromagnetic wave propagating in the circular waveguide with a semiconductor obstacle placed on the waveguide wall. H_{01} (TM_{01}) mode that is frequently used in HPM pulse generation was considered.

We search for such electrophysical parameters of the obstacle that it can serve as the prototype of the SE for the circular waveguide RS. Considering the semiconductor obstacle from this point of view, the main requirements for it can be formulated. First, the SE should not insert a considerable reflection in the waveguide, so the value of VSWR has been set at < 1.2. Second, the RS should be able to measure nanosecond-duration HPM pulses; therefore, the DC resistance of the RS should not exceed 50 Ω. Third, the shape of the SE should be taken as a plate that is important for heat transfer from the SE. Finally, the flat frequency response of the RS in the waveguide's frequency band is desirable.

4.1 Layout of SE

We have investigated a semiconductor plate with metal contacts placed on the wall of the circular waveguide. The layout of the plate is shown in Figure 5. The obstacle looks as a sector of a ring placed on a wall of the circular waveguide with radius a. The height of the plate is h, the width measured at the midpoint of $h - d$ and the length of the obstacle in the wave propagation direction is l. Practical realization of the sensor is similar to the millimetre wave RS described in subsection 3.3. It consists of two separate rectangular parallelepiped shaped samples placed in a close proximity to each other. Their top contacts are shorted with a thin metal foil. The bottom contact of one of the SE is grounded while the other one is isolated from the waveguide and is used for the RS feeding and the output signal measurement.

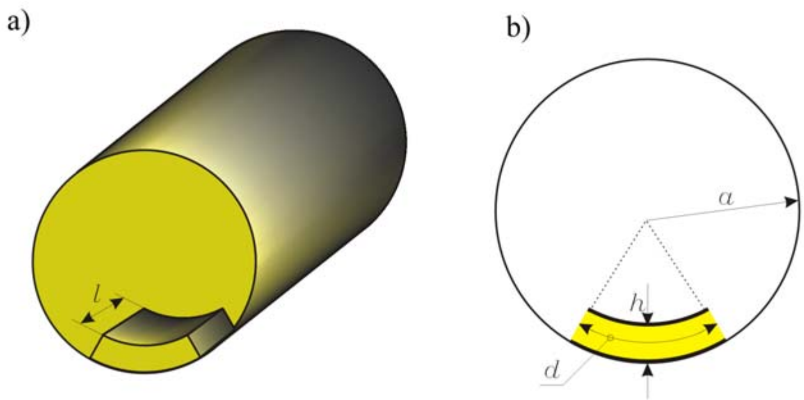

Figure 5: A plate of the semiconductor on the wall of the circular waveguide: a) 3-D view, b) a sectional view with a metal contacts on the top and bottom surfaces

4.2 Model and calculation results

We have performed FDTD simulations [4] in order to investigate the interaction of the regular H_{01} electromagnetic wave with the semiconductor obstacle. A cylindrical coordinate system was used. Although the regular H_{01} type wave has one electric field E_φ and two magnetic field components H_r and H_z, in a vicinity of the SE all electromagnetic field components might appear. Therefore, to determine the average electric field amplitude in the semiconductor obstacle Maxwell's equations have to be solved computing all six components of the electric and magnetic fields.

Calculations have been performed for the waveguide with the inner radius $a = 2$ cm. For such waveguide the cutoff frequency for the H_{01} mode is $f_c = 9.14$ GHz. We performed calculations starting from $f = 10.2$ GHz ($f_c/f = 0.9$) towards higher frequencies. Calculations have been performed for different sets of dimensions and specific resistance of the obstacle. When calculating sensors sensitivity (6) the dependence of the effective warm-electron coefficient on frequency was not taken into account, therefore our findings can be used at lower frequency, up to and including X-band.

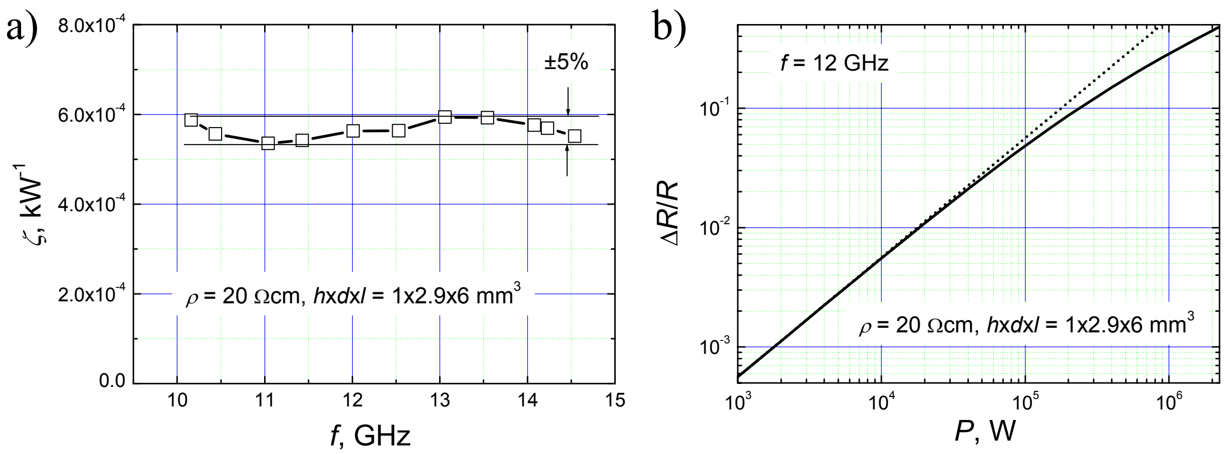

Figure 6: The dependence of the sensitivity of the optimal RS on frequency (a) and dependence of the relative resistance change on power transmitted through the waveguide at f = 12 GH: solid line shows result calculated using (4), dotted line demonstrates linear dependence that is characteristic of the warm electron region

The metal contact on the top of the SE effectively prevents to the penetration of the regular component E_φ into the bulk of the obstacle. Therefore, average electric field in the obstacle consists mainly of E_r component. It was found that some resonance, similar to that considered in subsection 3.3 for the millimetre wave RS, occur in the SE when increasing its length in a wave propagation direction. Therefore, the decrease of the electric field in the waveguide with frequency due to waveguide dispersion was compensated properly adjusting the position of the resonance in the frequency scale. At a moment, the optimal SE found should have the following electrophysical parameters: $\rho = 20\ \Omega\cdot$cm, $h\times d\times l = 1\times2.9\times6$ mm^3. Its total DC resistance is roughly 46 Ω. Calculated dependence of the sensitivity on frequency for the optimal RS is shown in Figure 6a. As one can see from the figure, a flat frequency response is characteristic of the optimal RS. The calculated sensitivity variation within frequency range 10.1–14.7 GHz is roughly ±5%. The considered frequency range corresponds to f_c/f = 0.9–0.62. Due to a small height, the optimal sensor does not perturb much the field distribution in the waveguide. Calculated VSWR slightly increases with frequency, but it is less than 1.05 within considered frequency range.

Once the electric field strength in the SE is determined, the dependence of the relative resistance change on a power transmitted through the waveguide can be calculated. For this purpose, expression (4) and parameters of n-Si presented in Table 1 are used. Calculations have been performed up to pulse power 2.2 MW, which is considered as limiting due to the breakdown of the air in the waveguide. Calculation results are shown in Figure 6b by the solid line. The dotted line corresponds to the linear dependence of $\Delta R/R$ on P that is characteristic of the warm electron region. It is seen that at a maximum power roughly 50% relative resistance change of the SE is observed.

It is worthwhile mentioning that the resistance change, in general, should influence the average electric field in the SE. Our calculations at 12 GHz have revealed that the increase of specific resistance 1.5 times imposes the increase of the average electric field in the SE by a factor 1.17. Therefore, the actual average electric field in the SE will be enhanced by electron heating effect but this effect is not so large in this particular case. Nevertheless, calculated dependence of $\Delta R/R$ in a high power limit should be considered as some approximation useful to estimate relative resistance change of the RS in the HPM region.

Since Maxwell's equations are linear, the dimensions and specific resistance of the optimal SE in the frequency range f_c/f =0.9–0.62 can be easily recalculated for the lower frequency bands using following dimensionless parameters of the optimal RS: $h/a \times d/a \times l/a = 0.05 \times 0.145 \times 0.3$ and $\rho/a = 10\ \Omega$.

5.0 CONCLUSIONS

Presented overview on the resistive sensors, based on electron heating effect in semiconductors, strongly suggests that they are one of the most perspective devices for HPM applications. The RS can measure 40-60 dB higher pulse power in comparison with a conventional diode. It can be used in a wide frequency range were at a moment powerful HPM pulse sources are designed and manufactured. The RS demonstrates very good long-term stability. It is resistant to large power overloads. Using the DC pulse supply for the RS feeding, an output signal up to a few tens of Volts can be obtained without any amplification circuit. The resistive sensors can be done sufficiently fast to measure microwave pulses with a duration on the order of a few tens periods of microwave oscillations. Making use the increase of the electric field in the sensing element with frequency due to a resonance phenomena, sufficiently flat frequency response of the RS in the waveguide's frequency band can be engineered, compensating not only decrease of the electric field due to waveguide dispersion but also the decrease of the electron heating effect with frequency.

6.0 ACKNOWLEDGEMENTS

The Lithuanian State Science and Studies Foundation supported this work through the programs "Sensors" and "Advanced Millimetre-Wave Electronics". Effort was sponsored by the Air Force Office of Scientific Research, Air Force Material Command, USAF, under grants numbers F61775-02-WE030, FA8655-04-1-3047, FA8655-07-1-3028. The authors would like to thank Dr. T. Anbinderis, General Director of Joint Stock Company "Elmika", Vilnius, Lithuania for the fruitful cooperation in testing of the millimetre wave resistive sensors.

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