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Plasma formation during solid-body irradiation by microwaves and its application for localizing the energy input

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Abstract. Problems associated with the thresholds for plasma production (and connected with it, the nonlinearity of microwave energy release) during irradiation of complex metal–dielectric targets by microwaves in a deep vacuum or in a high-pressure gas were studied. The discovered effect of the low threshold for plasma formation, for which no adequate model exists, may find a number of applications, in particular, in quasi-stationary current generation, gas-discharge rocket engines and microwave soldering.

1. Introduction

Microwaves are finding increasingly broad applications in solving engineering problems. Mainly, they are used in the following fields: heating of dielectric materials (industrial microwave ovens), wood drying, soldering and welding, vulcanization and polymerization, ceramics sintering and waste processing [1]. Among many other microwave applications, the methods involving pulsed radiation are especially interesting. The short action has some advantages, for example the possibility to apply a significant energy to an irradiated solid body (a target) in a time substantially shorter than the characteristic time of heat removal from the region of the energy release.

Analysing the prospects for pulse microwave engineering, we must note that it does not virtually involve a wide range of materials including all metals and dielectrics which are transparent to microwaves. The evident difficulty in treating such materials is associated with a low efficiency of conversion of the microwave energy into heat energy.

The microwave radiation intensity I_f (W cm^{-2}) needed for a specific energy input q (J cm^{-3}) into a dielectric can be estimated from the relationship [2]

$$I_f = 2.7 \times 10^9 q/(\omega \varepsilon \tau_f \tan\delta) \qquad (1)$$

where ω is the microwave cyclic frequency (in reciprocal seconds), ε is the dielectric constant of an irradiated material, $\tan\delta$ is the tangent of the loss angle of microwave radiation, and τ_f is the microwave-pulse duration (in seconds). In the case of metal–sample irradiation, the ratio between the microwave intensity and the specific energy release in the region of microwave penetration can be represented in the form [3]

$$I_f \approx cq\zeta/(\omega\tau_f\beta) \qquad (2)$$

where ζ is the depth of heat penetration into a sample in a time τ_f: $\zeta \approx (\chi\tau_f)^{1/2}$; χ is the temperature conductivity of metal, $\beta = c/(2\pi\sigma_t\omega)^{1/2}$ is the depth of the skin layer and σ_t is the conductivity of the metal.

As follows from (1), fairly intense microwave radiation is needed to attain noticeable specific energy releases in irradiated samples such as a dielectric with a small value of $\tan\delta$ (quartz, Teflon, polystyrene and so on). According to (2), this is true for essentially all metals.

Relationships (1) and (2) have been obtained in terms of linear electrodynamics, in which the ratio L_f/q is assumed to be independent of the level of the applied microwave power. however, from the general physics standpoint, we can expect that, when the intensity I_f reaches sufficiently high values, there will arise nonlinear effects, which drastically change the laws of microwave energy absorption. The most evident mechanism for nonlinearity can be associated with the onset of the

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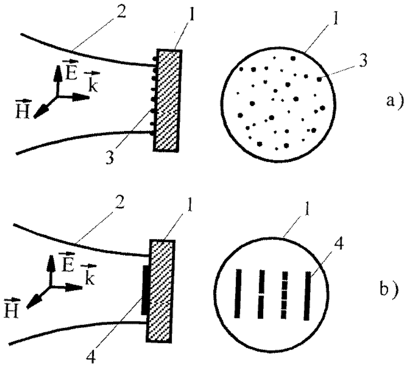

Figure 1. A schematic diagram of irradiation of an ‘open’ metal–dielectric target: (*a*) metallic spheres introduced into a dielectric surface and (*b*) a system of thin dipoles introduced into a dielectric surface. 1, dielectric target; 2, microwave beam; 3, metallic spheres; and 4, metallic dipoles.

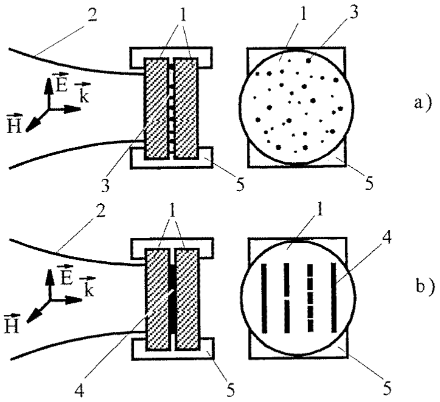

Figure 2. A schematic diagram of irradiation of a ‘sandwich’-type metal–dielectric target: (*a*) metallic spheres clamped between dielectric plates and (*b*) thin dipoles clamped between dielectric plates. 1, dielectric plates; 2, microwave beam; 3, metallic spheres; 4, metallic dipoles; and 5, dielectric clamp.

sublimation processes accompanied by vapour ionization and the appearance of a plasma near the surface of an irradiated sample.

The threshold for the appearance of such nonlinear processes can be estimated from formulae (1) and (2), in which q denotes the value of the sublimation energy of the target material ($q \approx q_s$).

For example, during irradiation of Plexiglass by pulsed microwaves ($\lambda_f \approx 1$ cm) with a pulse duration $\tau_f = 100\ \mu$s, we find (assuming that $q_s = 1$ kJ cm^{-3}, $\varepsilon = 2.6$ and $\tan\delta = 8\times10^{-3}$) that the threshold (with respect to the onset of the sublimation process) intensity is as large as

$$[I_f]_{th} \approx 10^7\ \mathrm{W\ cm^{-2}}. \qquad (3)$$

We can readily show that, for these values of microwave intensity, the level of electric fields is actually higher than the threshold both for target vapour breakdown and for the formation of a near-surface plasma.

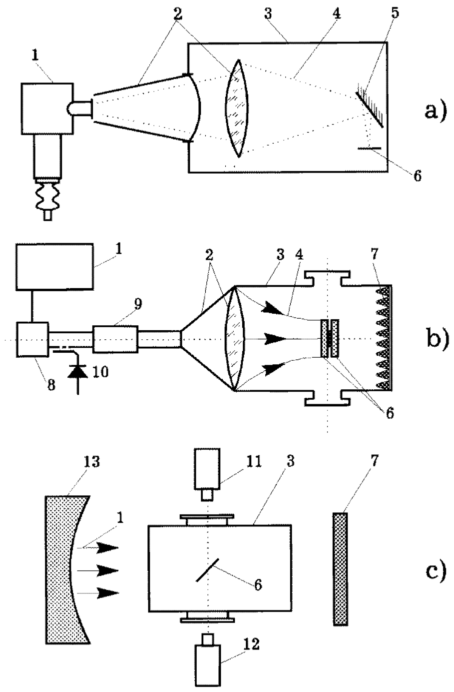

Figure 3. A schematic diagram of the experiment. (*a*) The ‘SWECHA’ installation: 1, gyrotron; 2, horn-lens antenna; 3, vacuum chamber; 4, microwave beams; 5, metallic mirror; and 6, metal–dielectric target. (*b*) The ‘MOSKWA-3’ installation: 1, modulator; 2, horn-lens antenna; 3, vacuum chamber; 4, microwave beam; 6, metal-dielectric target; 7, microwave absorber; 8, magnetron; 9, circulator; and 10, detector of microwave power. (*c*) The ‘X’ installation: 1, microwave beam; 3, vacuum chamber; 6, metal–dielectric target; 7, microwave absorber; 11, the Thermovisor AGA-680 device; 12, photomultiplier; and 13, antenna.

Considering metals and assuming, as earlier, that $\tau_f = 100\ \mu$s, we find the depth of the heating region to be of order

$$\zeta \approx 10^{-2}\ \mathrm{cm}$$

(because the temperature conductivity for metals is $\chi \approx 1$ cm^2 s^{-1} [4]). The specific energy needed for metal sublimation is $q_s \approx 10$ kJ cm^{-3} [4]. For silver, we have $\sigma_t \approx 6\times10^{17}$ in CGS units and assuming that $\omega = 2\times10^{11}$ s^{-1} yields $\beta \approx 0.3\ \mu$m. Hence, from relationship (2), it follows that

$$[I_f]_{th} \approx 5\times10^9\ \mathrm{W\ cm^{-2}}. \qquad (4)$$

This value is substantially higher than that for the dielectric.

For $\tau_f \geq 100\ \mu$s, modern microwave engineering does not allow radiation intensities in the cross section with linear sizes about λ_f to be higher than 10^5 W cm^{-2} [5]. Hence, according to this, it is virtually impossible to realize the conditions for irradiation of microwave-transparent dielectric or plane metal samples which result in the generation of a near-target plasma.

We can see that the situation with irradiation of uniform metal or dielectric targets is rather predictable. At the same time, the problems of complex targets,

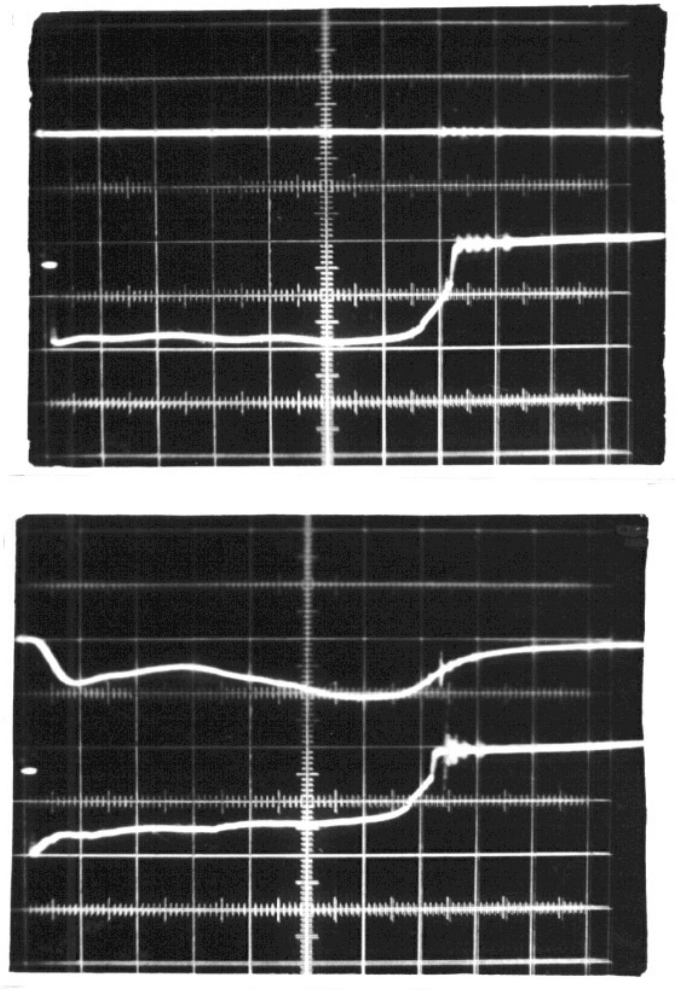

Figure 4. A metal–dielectric target irradiated by a microwave beam in the air at atmospheric pressure in the 'X' installation. The oscillograms are of signals from the detector of transmitted microwave radiation (*a*) and (*c*) and from the photomultiplier (*b*): (*a*), without discharge; (*b*) and (*c*), with discharge. The scale is 100 μs per division.

consisting of elements with different values of conductivity (for example, a combination of metals and microwave-transparent dielectrics) have not been treated yet. When we started this work, neither general physics considerations nor obtained experimental data permitted us to give unique solutions to such problems as the thresholds for plasma formation, the influence of materials and geometry of metal–dielectric compositions on these thresholds, microwave radiation polarization and so on. At the same time, these problems became urgent for modern engineering in connection with, for example, microwave soldering of dielectrics or semiconductors and designing output ports of powerful microwave generators.

Here, we report a study of the problems associated with the thresholds for nonlinearity of the microwave energy release (thresholds for plasma formation) when irradiated dielectric samples contain metal inclusions. We describe the experiments performed with a series of microwave devices at the General Physics Institute of the Russian Academy of Sciences and the Moscow Radiotechnical Institute. The results of measurements are discussed.

2. Description of the experiment and devices

The experiment is performed as follows. Plane metal–dielectric targets are irradiated by powerful microwave beams propagating freely in space. We determine the power level at which the radiation–target interaction ceases to be described by linear electrodynamics and is already governed by the nonlinear effects associated with plasma formation.

Most of the experiments were performed with the following two types of metal–dielectric compositions:

(i) Metal particles or thin strips (made of stainless steel, silver, cadmium, tungsten, copper–silver solder and so on) are in one way or another fixed on the surface of a dielectric transparent to microwaves (such as Plexiglas, quartz, Teflon or glass). The metal–dielectric surface is open and oriented towards the source of microwave radiation (see figure 1). Metal particles have either a regular spherical shape or an arbitrary geometry. For all the experiments the relationship

$$\beta \ll l_p \ll \lambda_f \tag{5}$$

holds. Here, l_p is the characteristic size of a particle, λ_f is the wavelength of microwave radiation. We chose

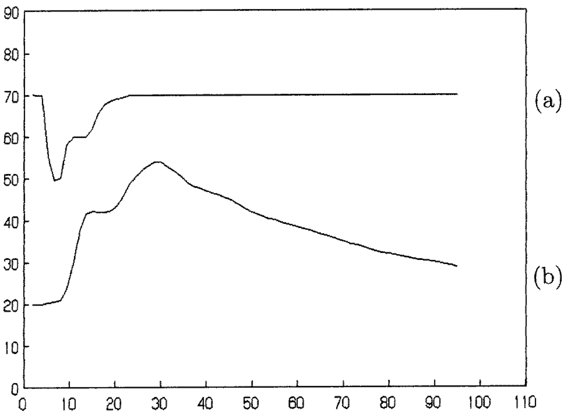

Figure 5. A metal–dielectric target irradiated by a microwave beam in the air at atmospheric pressure in the ‘X’ installation. The oscillograms are of signals from the detector of transmitted microwave radiation (*a*) and from the receiver of IR radiation (*b*). The x-scale is 500 μs per division, $I_f \approx 10^4$ W cm^{-2} and τ_f = 400 μs.

the average distance between the particles d^* so that, in the case of a low microwave power, the coefficient of transmission through the metal–dielectric composition is fairly high (usually it is as high as $\geq$ 50%). In experiments, we used a broad range of particle sizes from 0.5 mm to less than 100 μm. The longitudinal size of metal strips (dipoles) was either resonant with the wavelength of the incident microwave radiation or arbitrary. The width (l_d) and the thickness (Δ_d) of the dipole also satisfied the relationship

$$\beta \ll l_d \qquad \Delta_d \ll \lambda_f. \tag{6}$$

(ii) For the second type of metal–dielectric composition, metal particles were clamped between two microwave-transparent dielectric plates as shown in figure 2 (the ‘sandwich’ variant). Hence, the microwave radiation reached the metal–dielectric elements only after passing through the additional (to the first variant) layer of a homogeneous dielectric.

The metal–dielectric compositions of both open and sandwich types were irradiated by beams of focused pulsed microwave radiation, in which the electric field vector $\boldsymbol{E}$ was parallel to the irradiated surface. A typical schematic diagram of the experiment is shown in figure 3.

The microwave beam was introduced into a metal cylindrical chamber, which is either pumped out to a high vacuum ($p \leq 10^{-4}$ Torr) or filled with a working gas at pressures reaching the atmospheric one. Metal–dielectric targets were located in the focal plane of a converging Gaussian beam.

Experiments were performed with several microwave installations at the General Physics Institute (‘SWECHA’ and ‘MOSKWA-3’) and at Moscow Radiotechnical Institute (‘X’). A detailed description of these devices has been given in [6–8]. Table 1 lists the parameters of the microwave generators.

Usually, the sizes of metal–dielectric targets were several times larger than the transverse dimensions of the microwave beam. In experiments we used the following diagnostics:

(i) recording of the microwave radiation passing through the target;

(ii) recording (by photomultiplier) the luminescence of a plasma arising near the surface of an irradiated target;

(iii) determining the thermal image for the surface of irradiated specimens from IR radiation (using an AGA-680 thermovision device); and

(iv) photomicrography of the surface of a metal–dielectric target irradiated by a sequence of microwave pulses.

3. Experimental results

Experiments, performed according to the schematic diagram of figure 3 in a broad range of initial gas pressures (from high vacuum to atmospheric pressure), have shown that, starting with certain threshold powers, the action of the pulse microwave beam on a metal–dielectric surface is accompanied by the generation of a near-surface plasma. This plasma changes the behaviour of the energy release in a target and yields a nonlinear dependence of the energy input on the level of the incident power.

The threshold for plasma formation is determined both by the specific light burst near the surface of a target and by the attenuation of the transmitted microwave radiation. Figure 4 displays typical oscillograms obtained from a microwave detector and a photomultiplier following the light emission from the surface of a metal–dielectric target. We used also the recording system of an AGA-680 thermovision device in order to compare the time evolution of light in the infrared spectrum with that of the microwave passing through the target (figure 5).

Figures 4 and 5 show the correlation between the bursts of visible and IR light and the reduction in the level of the passing microwave power. Discharge formation starts either when the light intensity begins to increase or when the transmitted microwave radiation weakens.

Figure 6 displays typical photographs of the surface discharge in the case of the threshold being exceeded for a ‘sandwich’-type target with ball-like metal elements of diameter 300 μm. The target was irradiated in air at atmospheric pressures.

Figure 7 presents a typical photograph of a part of a metal–dielectric surface which was multiply irradiated by a pulsed microwave beam (a 300-fold increase). One can see typical traces of the dielectric–substrate sublimation at the points of crossing with a metal particle (a ‘crater’ around the metal element).

The main experimental results are the following.

(i) For all the specimens, tested both in open and in ‘sandwich’-type targets, the threshold for plasma formation turned out to correspond to the range of microwave radiation intensity $[I_f]_{th} \approx 2 \times 10^2$ to 10^4 W cm^{-2}, at least several orders of magnitude lower than that expected for uniform metal or dielectric targets (see (3) and (4)).

(ii) The thresholds for plasma formation depend weakly on the wavelength of microwave radiation, the type of its

Table 1. Parameters of various devices.

Device	Type of generator	Wavelength (cm)	MW pulse duration (μs)	Peak power (kW)	Peak intensity in a focal plane (kW cm^{-2})	Repetition frequency (Hz)
SWECHA	Gyrotron	0.8	≤ 100	≤ 400	≤ 30	≤ 5
MOSKWA-3	Magnetron	2.5	≤ 100	≤ 500	≤ 10	≤ 100
X	Klystron	4.0	1–760	≤ 3000	≤ 30	≤ 10

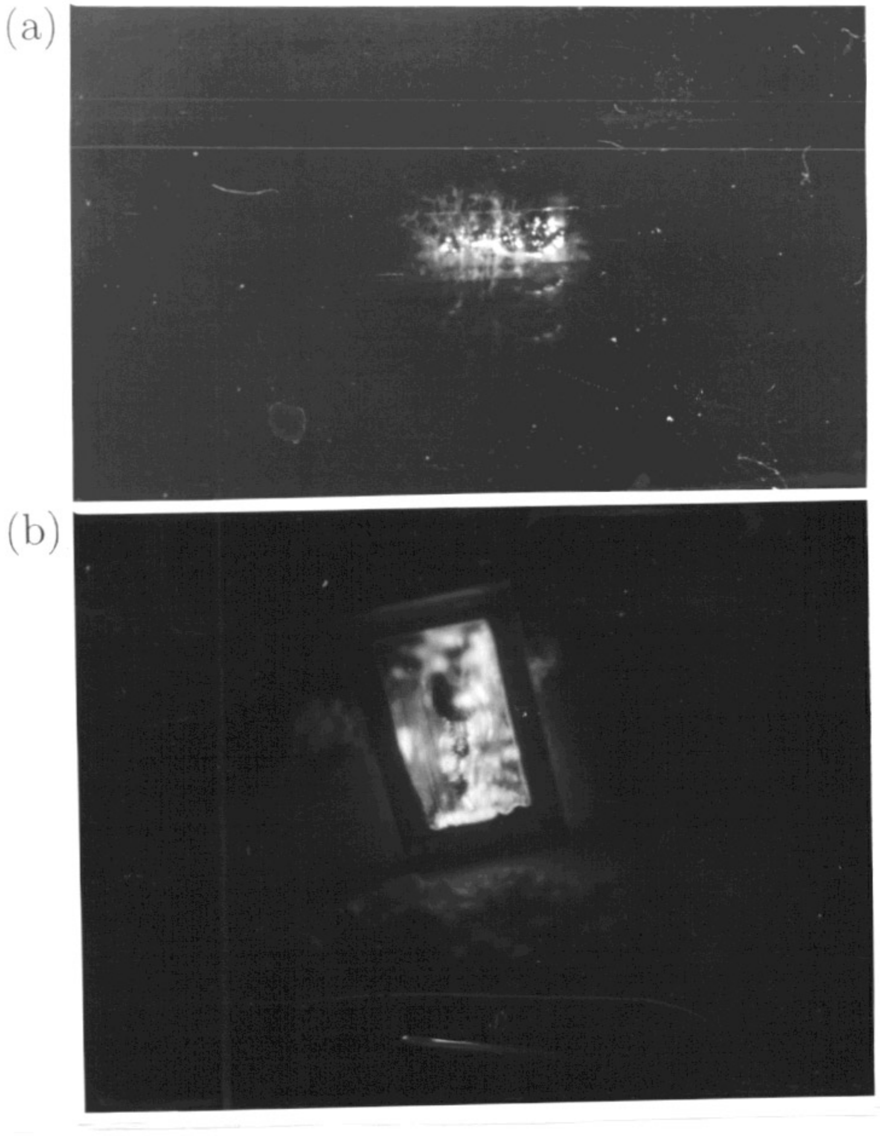

Figure 6. Photographs of a microwave discharge at atmospheric pressure on the ‘sandwich’ with micro-particles of molybdenum (*a*) and silver (*b*), in the ‘SWECHA’ installation.

polarization (linear or circular) and the material of dielectric and metal elements. The dependence on the system’s geometry (the sizes of metal elements, their shape and the distance between them) turned out to be the strongest.

(iii) The lowest thresholds for plasma formation were recorded in the case in which the metal elements were chosen as thin resonant dipoles (solid and cut).

(iv) The metal–dielectric interface is a particularly source of plasma formation. In the case of strip-like metal inclusions, the plasma was generated over the entire surface of the strip. When we utilized irregularly shaped metal particles or metallic balls, we observed frequent plasma

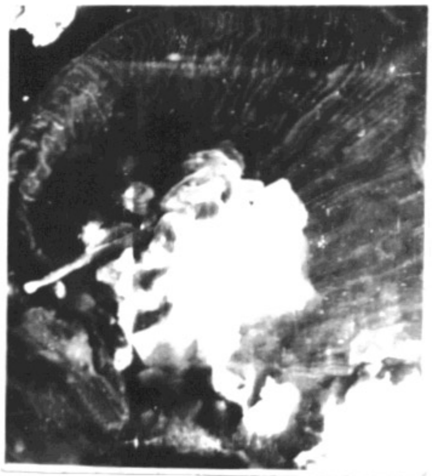

Figure 7. A photograph of a part of a metal–dielectric surface (including the metal particle at the centre of the photograph) after irradiation by a sequence of microwave pulses (enlarged by the factor 300).

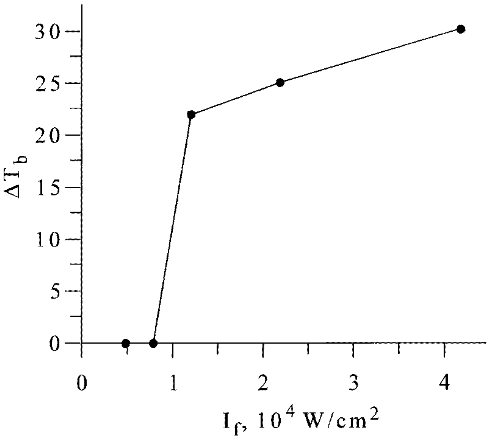

Figure 8. The dependence of the brightness temperature growth at the surface of a metal–dielectric target on the intensity of microwave radiation in the 'X' installation.

production near the boundary surfaces of many inclusions (see figure 6).

The data on the temperature of irradiated specimens was obtained with an AGA-680 thermovision device recording infrared radiation of a heated object The thermovision determines the brightness temperature (T_b) from which the real temperature (T_r) can be calculated. The relationship between the real and brightness temperatures is [9]

$$T_r = \frac{C_2}{\lambda_i} \frac{1}{\ln\{\varepsilon_{\lambda i} \exp[C_2/(\lambda_i T_b)]\}} \tag{7}$$

where C_2 is a constant ($C_2 = 1.48$ cm °C), $\varepsilon_{\lambda i}$ is the emissivity and λ_i is the wavelength at which the brightness temperature is measured. The emissivity can be determined from the relationship

$$\varepsilon_{\lambda i} \approx 1 - \exp(-d_p/l_{IR}) \tag{8}$$

where d_p is the depth of heat penetration in a substrate during the energy release and l_{IR} is the absorption length of infrared radiation in a substrate.

Figure 8 illustrates the typical dependence of the brightness temperature growth at the surface of a metal–dielectric target on the intensity of microwave radiation (the data are obtained from the experiments with the 'X' installation). It can be easily seen that, before reaching the threshold intensity (about 10^4 W cm^{-2}), the temperature growth in a microwave pulse is so small that it cannot be recorded by a thermovision device. When overcoming the threshold of plasma formation, the temperature increases abruptly and changes weakly with further growth in microwave power. Hence, these measurements clearly show the role of plasma formation both in the microwave energy conversion into the heat of the target and in the transition to the stage when the dependence of the energy release on the microwave power becomes nonlinear.

Figure 9 shows an oscillogram of a signal coming from the detector of the AGA-680 device when we scanned the vision region along the 'sandwich'-type target with a silver strip clamped between the two quarts plates. When the breakdown threshold is overcome, the glow arises over the entire surface of the strip. This glow is associated with plasma formation at the metal–dielectric interface. According to this oscillogram, which was obtained after a series of microwave pulses, the temperature of a metal strip turns out to be significantly (at least by an order of magnitude) higher than that of the quartz substrate.

4. Discussion of the experimental results

We evidently lack the experimental data to build an adequate physical model of the phenomenon. However, using the results described above, we can propose some hypotheses for the nature of the surface microwave discharge in metal–dielectric systems. Thus, it cannot be excluded that an important role in the observed low-threshold is played by the electron fluxes injected from the metal to the conductivity region of a dielectric touching this metal. The electron emission can be increased due to the lowering of the potential barrier and also due to the increase in the electric field of an electromagnetic wave at the metal particles or at the edges of metal strips.

Electron injection into a dielectric substrate increases the dielectric conductivity in a narrow layer near the surface [10] and it becomes close to the semiconductor conductivity. The absorption of microwave power in a dielectric with enhanced conductivity is accompanied by heating. Both the conductivity of the dielectric surface and the value of the injected electron flux grow with the temperature of the metal–dielectric interface. Consequently, the energy release in the interface region may be explosive in nature as a result of the onset of the thermal instability [10] accompanied by the phase transition of a solid body into a plasma.

The problem of sustaining the discharge after the surface breakdown should be studied separately. Under vacuum conditions, the problem is only that of the interaction between microwave radiation and a collisionless

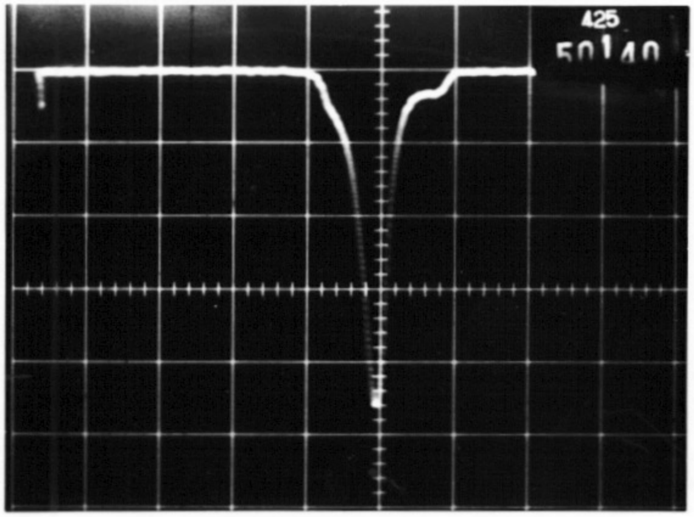

Figure 9. An oscillogram of the signal from an IR recorder scanning the field of sight along the surface of a metal–dielectric target (a thin dipole on the surface of the quartz plate). The scale along the horizontal axis is 1 cm per division.

plasma with smooth (in the case of an open surface) or sharp (in the sandwich case) boundaries. A complex and interesting physics of this phenomenon was, in particular, studied in [11, 12], which showed the contribution of nonlinear processes arising in the plasma-resonance region (in which the cycle frequency of microwaves is equal to the Langmuir eigenfrequency of the plasma) to the microwave radiation absorption and conversion of its energy into the energy of the electron component.

When a target is irradiated in a high-pressure gaseous mixture, the mechanism for the gas discharge excitation near the surface and its maintaining may be governed by the physical processes arising in the initiated high-pressure microwave discharges which were studied and described in [6]. This study shows that discharge production and maintenance is significantly influenced by the ionization through ultraviolet radiation from the surface of the target or from the constricted regions of gas breakdown.

The problem of the surface breakdown of metal–dielectric targets and of maintaining the discharge in the medium surrounding the target is of special interest and its solution requires specific experimental and theoretical studies. However, it is useful to note that, even now, there are quite a number of applied fields in which the phenomenon observed and described in this paper can be successfully used. Let us consider some of them.

4.1. Conversion of the powerful microwave radiation energy into the energy of a quasi-stationary current

The experiments performed at the GPI have shown that the microwave flare excited near the surface of a solid body in vacuum may efficiently induce the conversion of the microwave energy into the energy of a quasi-stationary current [11]. Two nonlinear processes underlie this phenomenon: microwave energy absorption in the plasma resonance region and explosive emission on the electrode introduced into the microwave flare.

Metal–dielectric targets with a low threshold for plasma formation may be used as a convenient element of the converter. They may served as the source of a collisionless super-critical plasma which absorbs the microwave radiation producing this plasma and converts it into a quasi-stationary current (or one with an industrial frequency). In this connection, the compositions under consideration are of interest both for energy supply of satellites by means of powerful microwave beams [14, 15] and for the ground receivers in the systems of solar space stations [16].

4.2. Acceleration of a spacecraft

The plasma flare excited by a powerful microwave radiation near a spacecraft may be considered as a source of jet propulsion compatible with the plasma jets used in modern engineering [17]. At the same time, the microwave discharge initiated in a high-pressure gas also holds some promise as a source of jet propulsion [6].

In both cases, we assumed that the spacecraft without fuel is accelerated by powerful microwave beams producing the plasma. These beams are generated from the ground or from the space stations. In this connection, it is useful to study metal–dielectric targets as sources of a collisionless plasma or as an ignitor of externally sustained gas discharges in the air surrounding the spacecraft which is to be accelerated.

4.3. Microwave soldering of dielectric elements

A unique possibility of localizing microwave energy release in a plasma produced at the metal–dielectric interface may be applied for soldering dielectric elements. This method might be especially useful when the heating of the whole composition is undesirable because of the destructive thermal loading.

One of the most important applications of such plasma-microwave soldering is the connection of diamond windows

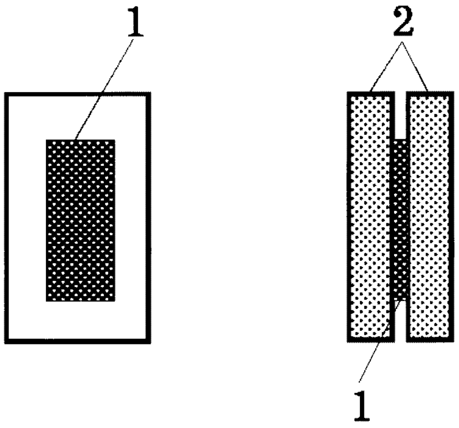

Figure 10. A ‘sandwich’-type target with a strip, made from metallic powder, clamped between two dielectric plates: 1, metallic powder; and 2, dielectric plates.

with the dielectric of semiconductor frames (such as SiC or Si_3N_4) by means of a silver–copper solder [18]. The use of thin silver–copper foil strips or a small-dispersion powder of this (or some other) solder allows us to expect pulsed metal heating (up to melting) when a composition similar to that shown in figure 10 is irradiated by a microwave beam with a power exceeding the threshold for plasma formation at the metal–dielectric interface.

Our experiments infer that it is possible to ignite the discharge (both in vacuum and in an atmosphere) in the case of a ‘sandwich’ when silver–copper strips or a small-dispersion powder of the same material are clamped between dielectric plates. This suggests that the proposed soldering technique can actually be used. The range of applicability for powerful pulsed microwave beams exciting the discharge at the metal–dielectric interface may turn out to be noticeably broader than the areas discussed above.

5. Conclusion

During the experiments we discovered new materials, namely, dielectrics with surface metal inclusions, which have a very low threshold for plasma formation under the action of microwave radiation. Consequently, the threshold for transition from the interaction described by linear electrodynamics to that described by nonlinear electrodynamics is also low.

We managed to excite the surface discharge at the intensity on the metal–dielectric surface $[I_{th}] \cong 10^2$–10^4 W cm^{-2} in a wide range of gas pressures ($10^{-5} \leq p \leq$ 700 Torr) during the irradiation by a pulsed microwave beam (wavelength varying in the range 0.8–4.0 cm and the pulse duration being $\tau_f \leq 100\ \mu$s). The discharge is excited both in the case of surfaces which are open to the microwave radiation and in the sandwich case in which the metal inclusions (strips, balls, irregular grains or small-dispersion powder) are located between two dielectric plates. Plasma production at the metal–dielectric interface allows us to localize the microwave energy release to an arbitrary prescribed point on the surface of a radiotransparent dielectric. The observed effect of the low threshold for plasma formation, for which no adequate model exists, may find a number of applications, in particular, in a transformer of microwaves into quasi-stationary current, gas-discharge rocket engines and microwave soldering.

References

[1] Sindoni E and Warton C (eds) 1992 *High Power Microwaves Generation and Applications ISPP-10 ‘Piero Caldirola’* (Bologna: SIF)

[2] Brandt A A 1963 *Investigation of Dielectrics at Super-High Frequencies* (Moscow: FM) (in Russian)

[3] Carslaw H S and Jaeger J C 1964 *Conduction of Heat in Solids* (Moscow: Nauka) (in Russian)

[4] Grigor’ev I S and Meilikhov E Z (eds) 1991 *Physical Quantities. Reference Book* (Moscow: Energoatomizdat) (in Russian)

[5] Benford J and Swegle J 1992 *High-Power Microwaves* (Boston: Artech House)

[6] Batanov G M, Gritsinin S I, Kossyi I A, Magunov A N, Silakov V P and Tarasova N M 1985 High-pressure microwave discharges *Plasma Physics and Plasma Electronics* ed L M Kovrizhnykh (New York: Nova) pp 241–82

[7] Kovrizhnykh L M (ed) 1994 *Physics and Chemistry of Gas-Discharges in Microwave Beams* (Moscow: Nauka) (in Russian)

[8] Batskikh G I and Khvorostyanoi Yu I 1992 *Radiotekhn. Elektron.* **37** 311–16 (in Russian)

[9] Kozelkin V V and Usol’tsev I F 1967 *Infrared Technics Foundations* (Moscow: Mashinostroenie) (in Russian)

[10] Vershinin Yu N 1968 *Solid Dielectric’s Electrical Breakdown* (Novosibirsk: Nauka) (in Russian)

[11] Kovrizhnykh L M (ed) 1988 *Nonlinear Waves and Quasi-stationary Current Generation in the Plasma* (Moscow: Nauka) (in Russian)

[12] Batanov G M, Ivanov V A and Kossyi I A 1984 Strong Langmuir turbulence and particle acceleration in the plasma corona *Nonlinear and Turbulent Processes in Physics* vol 1 (New York: Gordon and Porotch, Harward) pp 45–55

[13] Korolev Yu D and Mesyats G A 1984 *Auto-emission and Explosive Processes in the Gas Discharge* (Nov.: Nauka) (in Russian)

[14] Askar’yan G A, Batanov G M and Kossyi I A 1987 *Pis’ma Zh. Tekhn. Fiz.* **15** 17–23 (in Russian)

[15] Askar’yan G A, Batanov G M, Es’kov Yu M and Kossyi I A 1994 *Prikl. Fiz.* **2** 10–21 (in Russian)

[16] Vanke V A, Lopukhin V M and Savin V A 1977 *Usp. Fiz. Nauk* **123** 633–55 (in Russian)

[17] Batanov G M, Kossyi I A and Rabinovich M S 1979 *Pis’ma Zh. Tekhn. Fiz.* **5** 432–6 (in Russian)

[18] Bunn T L, Holly S, Koumvakalis N, Kossyi I A, Batanov G M and Kolesnichenko Yu F 1995 High power microwave *Contrib. Papers of SPIE Symp. (San Diego, USA)*