Transistor-Based Miniature Microwave-Drill Applicator

Yehuda Meir and Eli Jerby*

Faculty of Engineering, Tel Aviv University, Ramat Aviv 69978, ISRAEL

*E-mail: jerby@eng.tau.ac.il

***Abstract* — This paper explores the microwave self-focusing effect, and examines various new applications of transistor-based microwave-drills at <100-W microwave power range. The thermal-runaway instability is analyzed, and a drillability factor is defined heuristically for the minimal power needed to induce hotspots in specific materials. A practical transistor-based microwave-drill scheme using LDMOS-FET is introduced for delicate operations. Variants of this device are proposed for other applications, like local melting, ignition, indentation, plasma generation, and material identification by microwave induced breakdown spectroscopy (MIBS). Experimental results of glass processing, basalt melting and drilling, and thermite powder ignition are introduced as examples for future applications.**

***Index Terms* — Microwave ovens, microwave transistors, heating, melt processing, machining, spectroscopy, ignition.**

I. Introduction

The microwave-drill operation is based on the thermal-runaway interaction induced intentionally in the processed material by an open-end coaxial applicator [1, 2]. The hotspot evolved in the material due to its temperature-dependent properties [3] leads rapidly to local melting, and further to evaporation and plasma ejection [4]. The microwave-drill effect was demonstrated in materials like concrete, glass, ceramics, basalts, bones and silicon [5-10]. A similar device was studied also for silicon doping [11]. The microwave-drill capabilities were demonstrated mostly by magnetron tubes. Using instead solid-state microwave sources may reduce the size, weight, and complexity of the local heater, and improve its spectral characteristics, tunability and controllability.

Recent developments of gallium-nitride (GaN) and silicon-carbide (SiC) transistors have increased the available output power and efficiency well above 100-W and made them more relevant for heating purposes. Yet, the silicon-based laterally-diffused metal-oxide field-effect transistor (LDMOS-FET) [12], widely used in cellular base stations, is preferred here as a cost-effective and reliable microwave source also for local heating applications. Preliminary studies have shown the feasibility of low-power (<100-W) microwave heaters for delicate operations such as local heating [13], drilling [14], and soft-tissue treatments [15].

This paper studies the low-power range (10-100 W) of the localized thermal runaway instability, and proposes new applications for low-power transistor-based localized microwave heaters.

II. Experimental Transistor-based Setup

The experimental setup illustrated in Fig. 2 consists of a coaxial open-end applicator with a 1-mm$^{\varnothing}$ movable electrode fed by a solid-state amplifier with a positive feedback. The amplifier employs a single LDMOS-FET (Freescale MRF6S21140HR3 evaluation board). It is tuned by a feedback loop to oscillate at 2.1GHz, and has the capability to generate up to 140-W CW output power (a later version of this transistor exceeds 190-W output power). The transistor is protected from the reflected microwave power by an isolator in cascade. The output microwave power is controlled by the V_{GS} and V_{DS} voltages. The incident and reflected power levels are sampled by a directional coupler and detected by zero-biased Schottky diodes. A LabVIEW interface card samples the main operating signals, including the voltages and currents at the transistor's gate and drain, and the incident and reflected power levels.

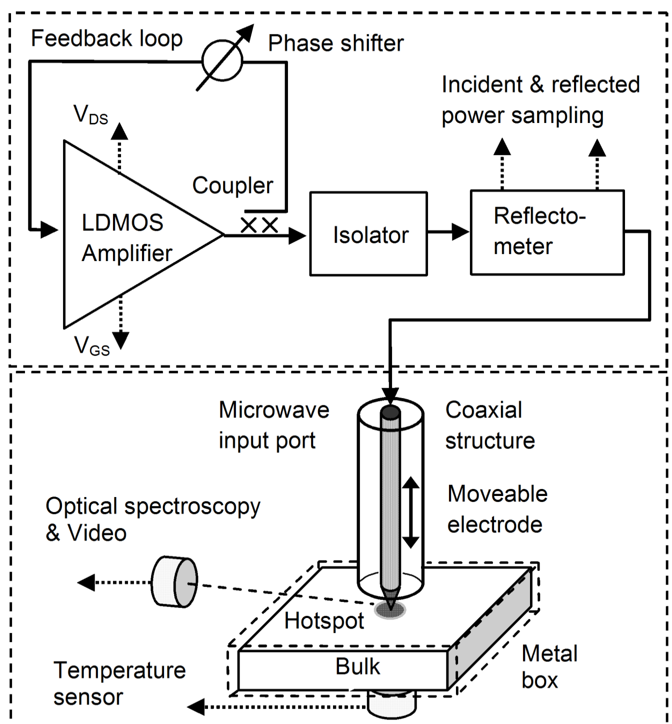

Fig. 1. The experimental transistor-based microwave-drill setup consisting of an LDMOS amplifier with a positive feedback loop feeding a coaxial open-end applicator with a movable center electrode.

The transistor-based microwave-drill apparatus was tested in local melting experiments of materials like glass, silicon, ceramics, and basalt. Figures 2a, b show an example of the low-power microwave drill impact on soda-lime glass. The hotspot induced in the 4-mm thick glass plate makes it porous in a confined region as shown in Fig. 2a. This porosity is easily removed by a slight mechanical grinding. Hence, the mechanically-assisted microwave drilling process includes repeating stages of applying the localized microwaves again on the same spot, cooling it down, and then removing the porous debris. This process results for instance in the ~3-mm$^{\varnothing}$ opening in the 4-mm thick glass plate shown in Fig. 2b.

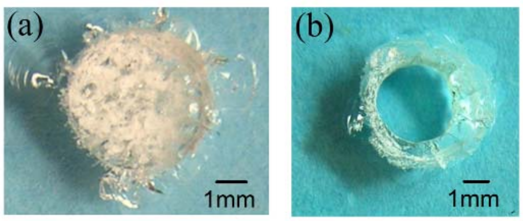

Fig. 2. Low-power (<100 W) microwave drilling in a 4-mm thick soda-lime glass plate: (a) A porous region is created by the localized microwave impact. (b) An opening is made by a slight mechanical grinding of the porous region, deepened repeatedly by microwaves.

The time-to-melt (TTM) parameter provides a unified measure for the induced thermal-runaway process in various materials. Figure 3 presents 25 experimental results of TTM measurements obtained in different microwave power levels in 1-mm thick glass plates. The incident microwave power, in the range of 50-110 W, was kept fixed in each run. The TTM measurements vs. power were fitted and compared to the theoretical model presented in the next section. The agreement between the experiments and theory is satisfying in the range of 60-110 W (<20% difference).

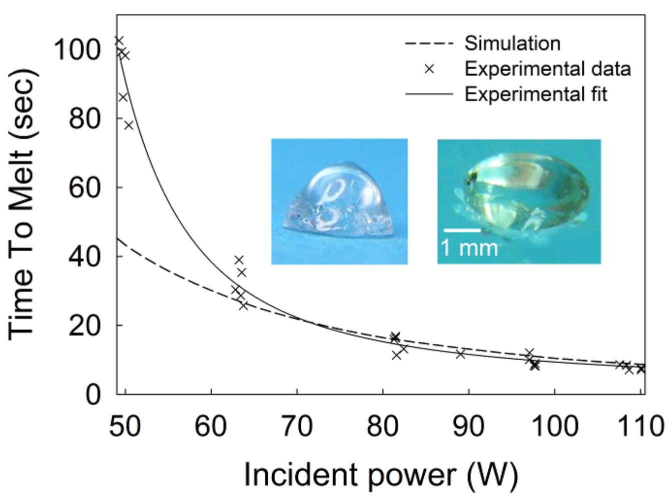

Fig. 3. Measured time-to-melt (TTM) values and their exponential curve fit ($a\exp[b/(x+c)]$) compared to the theoretical results for 1-mm thick soda-lime glass plate. The insets show the hole made (right) and the removed chunk of glass (left).

III. Coupled EM-thermal Model

The locally induced thermal-runaway instability is simulated by a coupled EM-thermal model for materials with temperature dependent properties [3]. The EM-wave and heat equations are presented in a two-time-scale approach by

$$\nabla\times\left(\mu_r^{-1}\nabla\times\tilde{\mathbf{E}}\right)-\left[\varepsilon_r'-j\left(\varepsilon_r''+\sigma/\omega\varepsilon_0\right)\right]k_0^2\tilde{\mathbf{E}}=0\,, \quad (1)$$

$$\rho C_p\,\partial T/\partial t-\nabla\cdot\left(k_{th}\nabla T\right)=Q\,, \quad (2)$$

respectively, where $\tilde{\mathbf{E}}$ is the electric vector component of the EM wave in the frequency domain, and ω and k_0 are its angular frequency and wave-number (in vacuum), respectively. The processed material is represented in Eq. (1) by μ_r, the relative magnetic permeability, $\varepsilon_r=\varepsilon_r'-j\varepsilon_r''$, the complex relative dielectric permittivity, and σ, the electric conductivity. In the heat equation (2), ρ is the local density of the processed material, C_p and k_{th} are its heat capacity and thermal conductivity respectively, and T is the slowly varying temperature. The material parameters, ε_r, σ, ρ, C_p, and k_{th}, may depend on the temperature.

The distinction between the typical time scales of the EM wave propagation (~1 ns) and of the much slower thermal evolution (>1 ms), allows the two-time scale approximation [3]. In addition, the operating EM frequency bandwidth is sufficiently narrow to neglect the permittivity's frequency dependence, hence the EM wave equations (1) is solved in these approximations in the frequency domain, while the heat equation (2) is computed in the slowly-varying time domain. Equations (1, 2) are coupled together by the local EM heating,

$$Q=\omega\varepsilon_0\varepsilon_r''(T)|\tilde{\mathbf{E}}|^2/2\,, \quad (3)$$

and by the consequent variation of the material's temperature-dependent parameters. As the temperature rises the spatial variations in ε_r and σ modify the microwave radiation pattern hence enhance the self-focusing effect.

Figures 4a-c demonstrate simulation results of a 1-mm thick soda-lime glass plate heated locally by 80-W microwave power at 2.1 GHz. The hotspot is evolved in a period of 17 s in which the glass reaches its softening temperature (~930 K) near the electrode. The electric field profile inside the glass is shown in a proportional vector plot in Fig. 4a. It reveals the dominance of the axial electric field component in front of the electrode tip, which exceeds $3.5\text{x}10^6$ V/m. The normalized heat flux vectors shown in Fig. 4b after the hotspot has been formed reveal the origin of the heat in a focal point located ~0.1 mm underneath the tip within the glass substrate (marked by a black arrow); hence the heat is induced locally by the microwave radiation directed by the tip. The temperature distribution (Fig. 4c) shows the hotspot confined in a 1-mm$^{\varnothing}$ region in front of the tip. The local-heating analysis identifies also an S shape bi-stable dependence of the temperature on the electric field, similarly to the S curve characterizing the thermal-runaway instability in volumetric microwave heating [16].

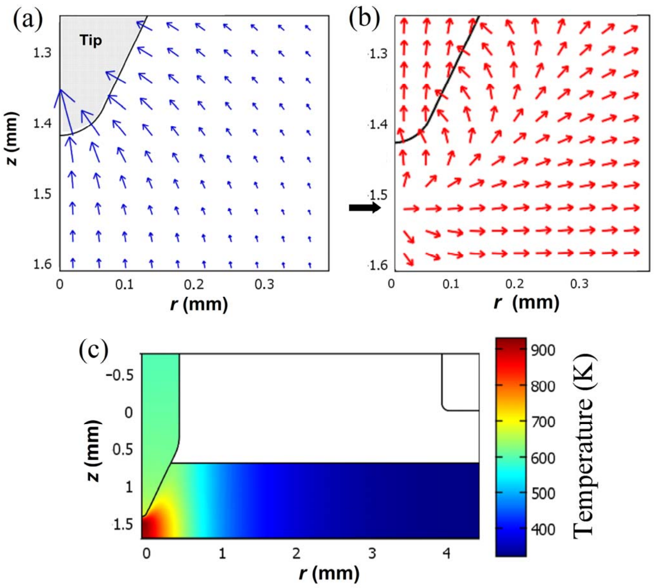

Fig. 4. Numerical simulation of the confined hotspot formed in a 1-mm thick plate of soda-lime glass irradiated by 80-W at 2.1 GHz for 17 s in which the glass reaches its softening temperature: (a) The electric-field vectorial distribution. The longest arrow in front of the tip represents the highest field of $3.5x10^6$ V/m. (b) The normalized heat flux in the vicinity of the drill bit. The resulted origin is marked by a black arrow. (c) The temperature distribution exceeding 930 K in front of the drill bit.

A simplified heuristic condition for the hotspot initiation is phrased in terms of power as $W>D$, where W is the net microwave power absorbed in the hotspot region. The parameter D is given by [17]

$$D = 2.5k_{th}\, d_{hs} \Delta T_m / \Delta\varepsilon_r'' , \qquad (4)$$

where ΔT_m is the difference between the melting and room temperatures, $\Delta\varepsilon_r''$ is the corresponding difference in the relative dielectric-loss factor, and d_{hs} is the hotspot diameter. The condition $W>D$ can be satisfied in microwave power levels of ~10-100 W for a variety of practical materials (except low-loss dielectrics like pure alumina or sapphire). This simple expression provides a rough estimate for the net minimal microwave power needed to initiate the induced thermal-runaway process hence it is regarded as a drillability factor in the context of the microwave drill operation.

For the sake of comparison, the numerical code was used to simulate the drilling operation in 1-mm thick slabs of mullite, glass, and Nylon™. Their drillability factors, 8.58 W, 0.92 W, and 0.05 W, respectively, reflect the different properties of these materials. Figure 5 shows the time-to-melt (TTM) parameter resulted from the simulation with respect to the microwave power applied to each material. In the power level relevant to solid-state generators, <100 W, the TTM is in the order of ~0.1 s for Nylon, 10 s for glass, and ~1 minute for mullite, in accord with the values of their drillability factor.

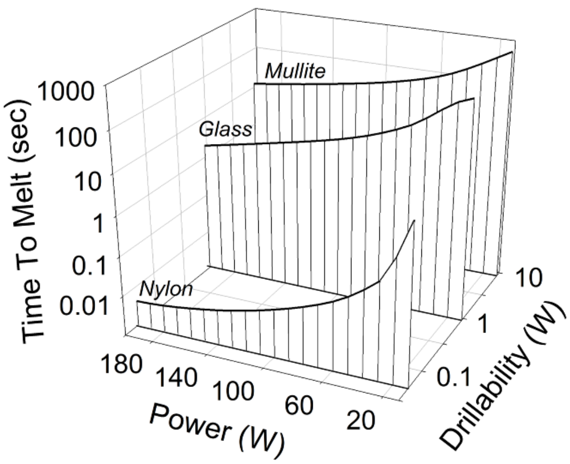

Fig. 5. The time-to-melt (TTM) values simulated numerically for Ertalon-6, soda-lime glass, and mullite, in different levels of microwave power, and their corresponding drillability factors [17].

IV. New Applications Of Localized Microwave Heaters

The local heating capabilities of the solid-state microwave-drill device may lead to a variety of applications and processes, as represented by the following examples:

A. Microwave-induced Breakdown Spectroscopy (MIBS)

The direct excitation of the hotspot and the slight plasma ejection by localized microwaves [4] enables the identification of the substrate material by atomic emission spectroscopy [18] as in the known laser-induced breakdown spectroscopy (LIBS) technique. Figure 6 shows spectra of copper, silicon and aluminum, generated and identified by the localized microwave-induced breakdown spectroscopy (MIBS).

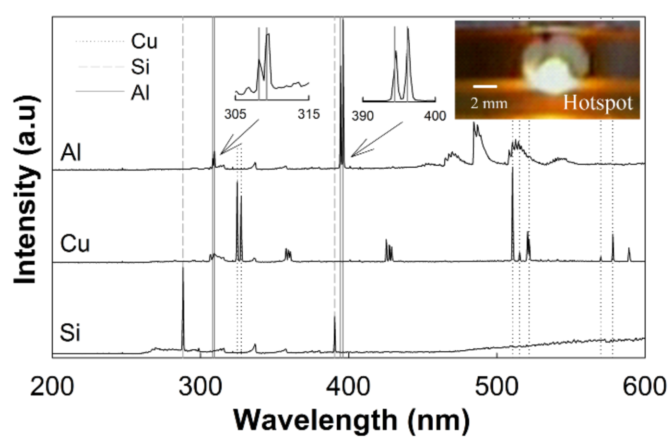

Fig. 6. Spectral measurements made by the localized microwave-induced breakdown spectroscopy (MIBS) of silicon, copper, and aluminum samples. The different materials are identified by their distinct atomic lines using an AES identification algorithm. The inset shows for example a plasma plume ejected from the surface of a soda-lime glass plate irradiated locally by 80-W microwave power.

The MIBS technique is proposed [18] as a low-cost substitute for the laser-based LIBS for material identification in scenarios in which a direct contact with the identified material and its slight destruction are permitted.

B. Thermite Ignition

Pure thermite is hard to ignite usually, but our study shows that it can be ignited directly by low-power localized microwaves. An ignition of Al-Fe_3O_4 thermite by <100 W microwave power is shown for instance in Fig. 7. The ~10-cm height thermite flame ejected from the combustion chamber can be used for various material processing. The combustion products in this case are regenerated iron and alumina.

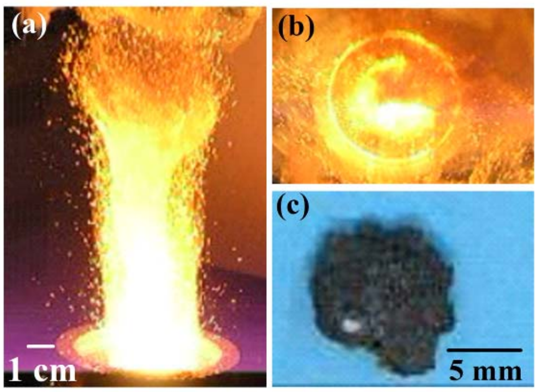

Fig. 7. Thermite of Fe_3O_4-Al mixture ignited by localized microwaves. Side and top views of the flame (a, b) and its iron and alumina products (c).

C. Indentation

The low-power microwave drill can be used for instance for shallow cuts in hard materials like basalts. Figure 8a shows melting of basalt by ~100 W localized microwaves, and nailing a 1-mm$^{\varnothing}$ bit into it. Figure 8b shows the letter **A** indented on a basalt brick by moving the microwave drill bit over its surface.

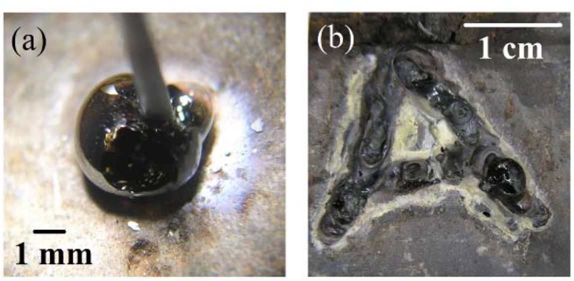

Fig. 8. Examples of microwave processing of basalt by a 100-W solid-state microwave drill: (a) Melting and nail insertion in a single step. (b) Indentation of the letter **A** on the surface of a basalt brick.

V. Conclusions

This study demonstrates the feasibility of localized rapid heating and melting of various materials by low-power localized microwaves. The new possibilities opened for delicate applications (e.g. drilling, indentation, identification, and ignition) can be implemented by low-cost devices, like LDMOS-FET microwave sources, in compact systems.

References

[1] E. Jerby, V. Dikhtyar, O. Aktushev, and U. Grosglick, "The microwave drill," *Science*, vol. 298, pp. 587-589, 2002.

[2] E. Jerby and V. Dikhtyar, "Method and device for drilling, cutting, nailing and joining solid non-conducting materials using microwave radiation," US patent No. 6,114,676, 2000.

[3] E. Jerby, O. Aktushev and V. Dikhtyar, "Theoretical analysis of the microwave-drill near-field localized heating effect," *Jour. Appl. Phys.*, vol. 97, pp. 034909-1-7, 2005.

[4] E. Jerby, A. Golts, Y. Shamir, S. Wonde, J. B. A. Mitchell, J. L. LeGarrec, T. Narayanan, M. Sztucki, D. Ashkenazi, and Z. Barkay "Nanoparticle plasma ejected directly from solid copper by localized microwaves," *Appl. Phys. Lett.*, vol. 95, pp. 191501, 2009.

[5] E. Jerby, V. Dikhtyar, and O. Aktushev, "Microwave drill for ceramics," *Amer. Ceramic Soc. Bull.,* vol. 82, pp. 35-37, 2003.

[6] X. Wang, W. Liu, H. Zhang, S. Liu, and Z. Gan, "Application of microwave drilling to electronic ceramics machining," *7th Int'l Conf. Electron. Packag. Technol.* Proc. Article # 4198945 (4 pages), ICEPT '06, August 26-29, 2006, Shanghai, China,

[7] E. Jerby, O. Aktushev, V. Dikhtyar, P. Livshits, A. Anaton, T. Yacoby, A. Flax, A. Inberg, and D. Armoni, "Microwave drill applications for concrete, glass and silicon," *Microwave and Radio-Frequency Applications 4th World Congress, Conf. Proc.,* pp. 156-165, Austin, Texas, November 4-7, 2004,

[8] Y. Eshet, R. Mann, A. Anaton, T. Yacoby, A. Gefen, and E. Jerby, "Microwave drilling of bones," *IEEE Trans. Biomedical Eng.*, vol. 53, pp. 1174-1182, 2006.

[9] E. Jerby and A.M. Thompson, "Microwave drilling of ceramic thermal barrier coatings," *Jour. Amer. Ceramic Soc.,* vol. 87, pp. 308-310, 2004.

[10] R. Herskowits, P. Livshits, S. Stepanov, O. Aktushev, S. Ruschin, and E. Jerby, "Silicon heating by a microwave-drill applicator with optical thermometry," *Semiconductor Sci. Tech.,* vol. 22, pp. 863-869, 2007.

[11] P. Livshits, V. Dikhtyar, A. Inberg, A. Shahadi and E. Jerby, "Local doping of silicon by a point-contact microwave applicator," *Microelectronic Eng.,* vol. 88, pp. 2831-2836, 2011.

[12] O. Latry, P. Dherbécourta, K. Mourguesa, H. Maananeb, J.P. Sipmab, F. Cornub, P. Eudelineb and M. Masmoudic, "A 5000 h RF life test on 330 W RF-LDMOS transistors for radars applications," *Microelectronics Reliability,* vol. 50, pp. 1574-1576, 2010.

[13] E. Schwartz, A. Anaton, D. Huppert, and E. Jerby, "Transistor-based miniature microwave heater," *Proc. IMPI 40th Annual Int'l Microwave Symp.*, Boston, pp. 246-249, 2006.

[14] O. Mela and E. Jerby, "Miniature transistor-based microwave drill," *Proc. Global Congress Microwave Energy Applications*, Otsu, Japan, pp. 443-446, 2008.

[15] A. Copty, F. Sakran, M. Golosovsky, and D. Davidov, "Low-power near-field microwave applicator for localized heating of soft matter," *Appl. Phys. Lett.*, vol. 24, pp. 5109-5111, 2004.

[16] G. A. Kriegsmann, "Hotspot formation in microwave heated ceramic fibers," *IMA Jour. Appl. Math.*, vol. 59, pp. 123-148, 1997.

[17] Y. Meir, M.Sc. thesis, Fac. of Eng., Tel Aviv University, 2010.

[18] Y. Meir and E. Jerby, "Breakdown spectroscopy induced by localized microwaves for material identification," *Microwave & Optical Tech. Lett.,* vol. 53, no. 10, pp. 2281-2283, 2011.