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BREAKDOWN SPECTROSCOPY INDUCED BY LOCALIZED MICROWAVES FOR MATERIAL IDENTIFICATION

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ABSTRACT: *This letter introduces a localized microwave technique for direct excitation of solid materials for the sake of their identification by atomic emission spectroscopy. The microwave energy is concentrated on the material surface by a microwave-drill type applicator. The evolved ∼1-mm^3 hotspot is slightly evaporated and excited as plasma. An optical spectrometer measures the atomic emission spectrum, hence enabling the material identification as in the known laser-induced breakdown spectroscopy (LIBS) technique. The experimental results demonstrate the conceptual feasibility of the localized microwave-induced breakdown spectroscopy as a low-cost substitute for the laser-based LIBS for material identification in scenarios in which a direct contact with the material to be identified and its slight destruction are permitted.* © 2011 Wiley Periodicals, Inc. Microwave Opt Technol Lett 53:2281–2283, 2011; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26272

Key words: *breakdown spectroscopy; atomic emission; microwave hotspot; plasma; microwave drill*

1. INTRODUCTION

Atomic emission spectroscopy (AES) [1] is commonly used to detect the elemental composition of materials by identifying the unique spectral structure of each element. The laser-induced breakdown spectroscopy (LIBS) technique [2] employs a short-pulse laser in order to ablate the material in a small spot on its surface and to cause its breakdown. The excited plasma is detected by an optical spectrometer in order to identify its elemental content by the AES analysis. The LIBS technique exhibits its unambiguous detection capabilities. Its development has been matured and it is implemented in commercial systems [3]. For some applications although the laser apparatus might be too expensive or complicated, cheaper or simpler techniques might be of interest. Microwaves have been used so far volumetrically for microwave-induced breakdown spectroscopy (MIBS) measurements in gases (e.g. [4–6]) and for assisting LIBS [7]. Here we present a MIBS technique for solids and liquids, using localized microwaves directly on the material surface.

In the localized MIBS technique presented here, the microwave-drill type applicator [8] plays the role of the laser beam in LIBS. This replacement is possible only in scenarios that allow a direct physical contact with the detected material [9]. The microwave drill concentrates the microwave energy into a hotspot of ∼1-mm diameter on the material surface by virtue of the localized thermal-runaway effect [10]. The microwave-drill type apparatus is used here only for the localized heating [11] without deepening the hole. The molten hotspot is further evaporated and ionized by the localized microwave field. This mechanism of plasma excitation directly from solids was demonstrated recently in dielectric [12] and metallic [13] substrates. Here we incorporate the microwave-drill type applicator with AES tools and demonstrate a localized MIBS technique for solids and liquids. Spectroscopic measurements and material identification using an algorithm based on National Institute of Standards and Technology (NIST) data [14] are presented, and the feasibility of the proposed localized MIBS concept is discussed.

2. EXPERIMENTAL SETUP

Figure 1 depicts the experimental scheme of the microwave-drill-based MIBS apparatus. The microwave-drill type applicator consists of a coaxial waveguide with a movable center electrode (a tungsten rod) that localizes the microwave energy into a confined region in the material due to the induced thermal-runaway effect [8, 10]. It is fed by an automatically tuned 2.45-GHz microwave generator with a variable output power in the range of 0–800 W (similar to the domestic microwave oven). The microwave drill interacts with the detected material in the contact point between the center electrode tip and the material surface, and it creates a molten hotspot of ∼1-mm diameter. By slightly pulling the center electrode out, while the microwave radiation is still on, a plasma plume is ejected from the hotspot. Figure 2 shows for instance a plasma plume generated in this localized microwave technique on the surface of a soda lime glass plate (4 mm thick) by applying 80-W microwave power to the applicator.

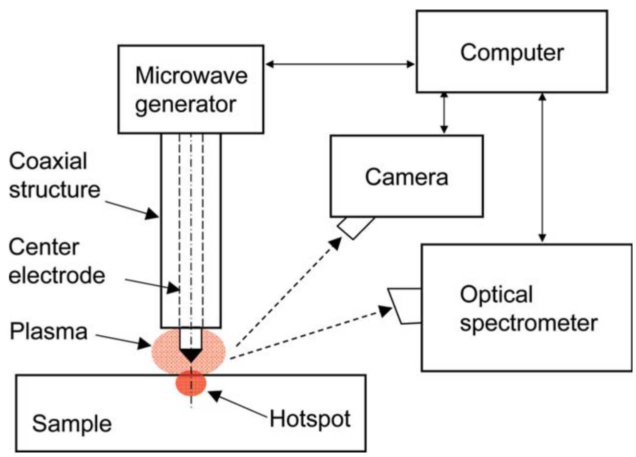

Figure 1 An experimental scheme of the localized microwave-induced breakdown spectroscopy setup used in this study. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

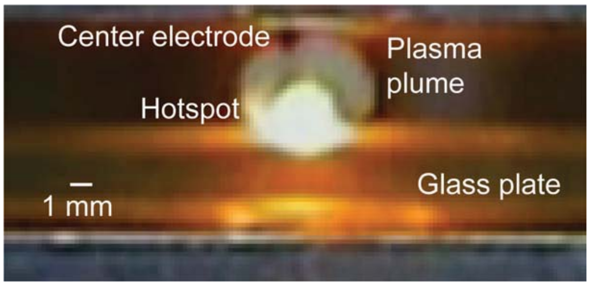

Figure 2 An example of a plasma plume ejected from the surface of a soda lime glass plate (4 mm thick) irradiated locally by 80-W microwave power. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

The image of the ejected plasma plume is captured by a digital camera and by a synchronized optical spectrometer (Avantes AvaSpec-3648). The system is operated by a LabView program that records the signals for the material identification analysis. The AES data are received from the optical spectrometer in a resolution of 0.34 nm and are analyzed by a Matlab code in order to identify the spectral lines observed. In this feasibility study, the technique is demonstrated for silicon, copper, and aluminum identification. The searching algorithm employs NIST data [14] taking into account the relative strength versus wavelength of each atomic line.

3. EXPERIMENTAL RESULTS

Figure 3 shows for instance the spectral evolution during the localized microwave interaction with a copper plate at 0.3 kW incident microwave power. The first period of ∼1 minute is characterized by a relatively low thermal radiation from the surrounding area and hence the background is negligible. The atomic spectral lines are clearly seen at the end of this period, and the AES measurement can be taken then. A further microwave heating intensifies the thermal radiation and increases the background level above the AES signal. Therefore, the MIBS measurement is limited to a certain period of the microwave-drill operation, marked as the *AES period* shown for instance in Figure 3.

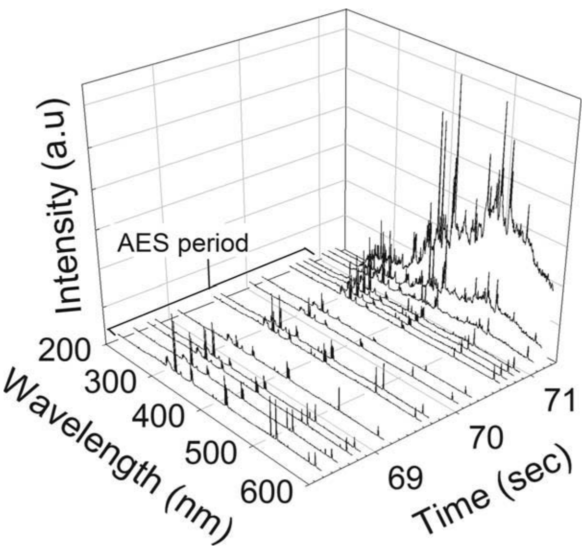

Figure 3 The spectral evolution during the localized microwave interaction with copper, as a typical example for the response of a material to be identified

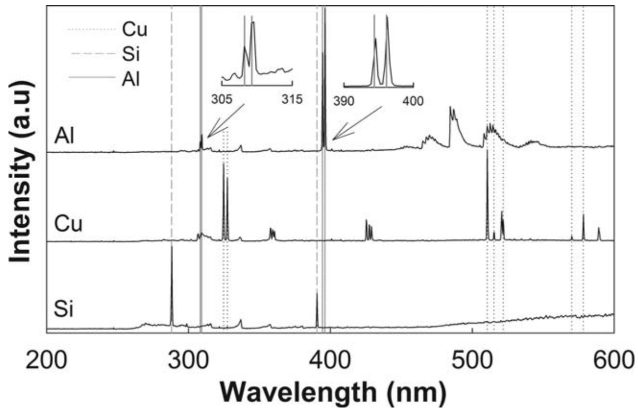

Figure 4 Spectral measurements made by localized microwave-induced breakdown spectroscopy of silicon, copper, and aluminum samples. The different materials are identified by their distinct atomic lines using an AES identification algorithm

Figure 4 shows spectral measurements of silicon, copper, and aluminum taken separately in the localized MIBS setup. The distinct spectral lines of the detected elements are clearly identified above the background. The latter includes the thermal blackbody radiation (shown in the silicon trace) and a slight emission from the microwave-drill tip due to its indirect heating. The spectral lines of these residues, e.g., tungsten and zirconium, are subtracted from the AES measurements to reduce the ambiguity (hence these elements cannot be identified). The AES identification algorithm also sets an intensity threshold (e.g., 1000 a.u. in Fig. 4) above which the spectral lines are considered as persistent and taken into account. Only these spectral peaks are detected and compared with the AES database [14].

The identification of the three elements shown in Figure 4 for instance is found as unambiguous. Neglecting the background lines below threshold, 13 prominent lines are detected altogether. Two of them are clearly associated with silicon, four with aluminum, and the other seven with copper (among which five lines are associated solely with copper in the entire visible spectrum).

4. DISCUSSION

The localized microwave technique based on the microwave-drill concept is applicable for materials with sufficient dielectric losses ε'' or electric resistively $1/\sigma$ to absorb the microwave energy. A heuristic condition for the microwave-drill applicability can be phrased as $W > D$, where W is the localized microwave power absorbed in the hotspot, and D is a thermal factor given by $D_D = 2.5k_{th}\left(d_{hs}\Delta T/\Delta\varepsilon''_r\right)$ and $D_M = 1.4k_{th}\sqrt{\omega\mu_0\sigma}\Delta T d_{hs}^2$ for dielectrics and conductors, respectively, where k_{th} is the thermal conductivity, d_{hs} is the hotspot diameter, ω is the microwave angular frequency, and ΔT and $\Delta\varepsilon'_r$ are the differences between the melting and the ambient temperatures and between the corresponding dielectric losses, respectively. This rough one-dimensional model is valid for dielectric wafers [11] and metallic foils [13]. The condition $W > D$ can be satisfied for most practical materials in reasonable microwave power levels, except for perfect dielectrics such as pure alumina or sapphire.

The localized MIBS concept differs from the LIBS technique in various aspects. The laser beam forms a narrower spot on the material surface and the LIBS ablation removes a layer of a few microns only, much smaller than the ∼1-mm^3 crater made by the microwave-drill type applicator. In this aspect, the MIBS based on localized microwave interaction is a slightly destructive technique. It also requires a physical contact with the detected material, which is not always possible. On the other hand, this MIBS system is much simpler, smaller, and cheaper than any LIBS system, because it utilizes low-cost microwave components and could be realized as a portable tool. Yet, the microwave-drill-based MIBS technique is not considered as a substitute for the LIBS technology but more likely as a low-cost extension for specific field applications.

The MIBS analyses and identification, demonstrated here by a simple algorithm, could be performed as well by various commercial programs with larger databases and more sophisticated algorithms available for LIBS systems. Such a program (e.g., AvaLIBS-Specline-A or similar) could be incorporated in the MIBS system to include additional elements.

Besides technical improvements (like extension toward IR and UV spectral ranges, increasing the sampling rate, and improving optical resolution and sensitivity), the localized microwave-based AES could be incorporated with additional spectroscopic methods such as atomic absorption spectroscopy and atomic florescence spectroscopy in order to verify the identification of the elements in the detected bulk material. Similar microwave excitation concepts might be considered also for the detection of larger molecules and even chemical or biological agents.

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A COMPACT CIRCULAR-RING ANTENNA FOR ULTRA-WIDEBAND APPLICATIONS

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ABSTRACT: *A simple circular-ring planar-monopole antenna, with a compact size of 26 × 28 mm^2, fed by an offset-microstrip line, is proposed. The antenna is composed of a circular-ring radiator and a ground plane with a small rectangular slot cut along the upper edge for ultra-wideband (UWB) operation. Studies of the antenna are carried out using computer simulation. Prototype of the antenna is used for verification of the simulation results. Results show that the antenna has an impedance bandwidth of more than 132% (from 3.7 to more than 18 GHz) for the standing wave ratio of less than 2 (voltage standing wave ratio, VSWR ≤ 2), a stable omnidirectional radiation pattern and an average peak gain of 3.97 dBi across the UWB, making the antenna a good candidate for use in UWB communications.* © 2011 Wiley Periodicals, Inc. Microwave Opt Technol Lett 53:2283–2288, 2011; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26295

Key words: *ultra-wideband; circular-ring antenna; planar antenna*

1. INTRODUCTION

With the increasing demands for high data rate transmission, broadband and multiband antennas play a vital role in the wireless communication world. Ultra-wideband (UWB) technology, with the advantages of low complexity, low cost, low spectral power density, high precision ranging, very low interferences, and extremely high data rates, has attracted much attention for high-speed wireless communication. Since the Federal Communications Commission released unlicensed band from 3.1 to 10.6 GHz for radio communication in 2002 [1], antennas with ultra-wide bandwidth have been widely investigated by both industry and academia. The design of efficient and small size antennas for wideband applications is still a major challenge. Many different designs of UWB antennas have been studied [2–14]. Some used the monopole configuration such as square, annual ring, triangle, elliptical, pentagon, and hexagonal antennas [2–10] and others used the dipole configuration like bow-tie antennas [11–14]. Most of these antennas either had relatively large sizes or did not have a real wide bandwidth. In this article, we propose a microstrip-fed planar-monopole antenna for UWB operation with a compact size only 26 × 28 mm^2, significantly less than those antennas reported in [2, 6–8, 10, 11]. Numerous methods have been reported to increase the bandwidth of UWB antennas, including increase of substrate thickness, use of a substrate with low dielectric constant, utilization of various feeding technique, and the use of slot antenna geometry [15, 16]. In general, the bandwidth and the size of an antenna are conflicting, i.e., improving one normally results in degradation of the other. Recently, techniques such as inserting additional stub to the one side of the circular patch [17], adding finite metal plane [3], adding slot to one side of the radiating element [18] and adding steps to the lower edge of the patch [19] have been reported to increase the impedance bandwidth of circularly and elliptically planar monopole antennas. In our design, the proposed planar antenna consists of a circular-ring radiator and ground plane with a small rectangular slot cut along the upper edge to increase the operating bandwidth. Measured results show that the proposed