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Inexpensive laser-induced surface modification in bismuth thin films

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ABSTRACT

In this work, we present results on texturing a 500 nm thick bismuth film, deposited by sputtering onto a glass slide using a low-cost homemade, near-infrared pulsed laser platform. A 785 nm laser diode of a CD–DVD pickup head was precisely focused on the sample mounted on a motorized two-axis translation stage to generate localized surface microbumps on the bismuth films. This simple method successfully transferred desired micropatterns on the films in a computer-numerical control fashion. Irradiated zones were characterized by atomic force microscopy and scanning electron microscopy. It was observed that final results are strongly dependent on irradiation parameters.

1. Introduction

Nowadays, laser processing is one of the most matured and direct techniques used in the field of micro and nanofabrication [1]. Laser direct writing is for instance a relatively simple technique to fabricate microstructures; it is based on interaction between a laser beam and a solid material [2,3]. Practically, micro and nanofabrication using lasers may be achieved with continuous or pulsed wave lasers [4,5]. In the latter case, the pulse duration is typically ranging from nanosecond to femtosecond [6–8] with repetition frequencies of up to a few MHz [9] and many different wavelengths from ultraviolet to infrared with a selection of colors in the visible domain [10–12]. Most of these high power lasers and ultrashort pulses are then used to modify the surface of a wide series of materials such as metals, semiconductors or dielectrics [13–15]. However, although the patterns resulting of this type of laser ablations present high resolution in the micron or submicron range, they always imply high inversion costs engendered by the laser equipment. In addition to that, they may require long experimental duration and complicated experimental setups, thus limiting their general accessibility.

Therefore, it is desirable to look for low-cost solutions offering the precision and control of laser systems to induce alterations such as ablation or surface modifications in the materials of interest. Laser direct microfabrication of polymers using a low-power, low-cost laser has recently been reported [16]. In this case, a simple compact-disk optical pickup head (PUH) has been used to etch materials with a low melting point or a low surface phase modification threshold. Bismuth is a semimetal with a melting point of 271 °C, which makes is a potentially good candidate for surface modification induced by low-power laser irradiation for device fabrication [17]. This semimetal is best known for its powerful applications mainly in the cosmetic and pharmaceutical industry and is widely used in the synthesis of organic compounds due to their low toxicity compared to other heavy metals [18,19]. Particularly, we are interested in thin films of this material because they occupy a prominent place in material research [20,21] not only for their well-known and extensive technological applications but also because their study provides tools for understanding the physical principles in which the material's properties are based. It has been reported for instance that laser interaction with a thin-film solid surface results in the formation of structures whose periodicity and geometry depend on experimental parameters such as laser irradiation and material properties [22–24]. These structures are called LIPSS (laser induced periodic surface structures) and have

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been widely studied since their applications cover a huge range of areas such as microelectronics, optics and biomedical technology [25–27]. Film thickness is also particularly important in surface modification and LIPSS formation and in this case the deposition technique employed to form the films must be well-controlled.

In this work we present preliminary results of laser-induced microstructuring of bismuth thin films by using a PUH extracted from a commercial CD–DVD burner. It was mounted on a motorized three-axis platform controlled in a computer numerical control (CNC) fashion. Optical and structural characterization of these microbumps has been achieved using scanning electron microscopy, atomic force microscopy and micro-Raman spectroscopy. It was observed that under optimized irradiation parameters it is possible to obtain LIPSS on bismuth using this low-cost alternative and the results are discussed in the following sections of this paper.

2. Experimental

The low-cost laser platform used in this work was detailed in [16] and is presented in Fig. 1. It consists of an optical pickup head (PUH) obtained from a commercial CD–DVD burner (Lightscribe Super Multi from LG Electronics), which is mounted on a platform with micrometric displacements in the *xyz* axis. This stage is motorized with stepper motors (Oriel Stepper Mike) that are controlled by a computer via a simple, practical user interface. The PUH consists of two laser diodes emitting at different wavelengths: 785 nm and 632 nm. In our case it was only possible to induce surface modifications to the bismuth thin layers using the NIR wavelength, due to a greater optical absorption coefficient at this wavelength. Indeed, it has been reported in [28] that the extinction coefficient *k* of Bi increases with the wavelength in the visible–NIR range. Higher power densities than those available in the PUH would then be required for the red laser.

The platform also offers to control the power density of the diode and to use it in either continuous or pulsed mode with pulse durations ranging from microseconds to continuous. The beam focused by the PUH is shone onto the sample and generates highly localized plasma visible as a laser-induced incandescence, causing a local surface modification of bismuth. By pulsing the laser at regular periodic intervals with the stepper motors, micron-sized conical structures are formed on the material, similarly to what is presented in [29]. The focused beam diameter is about one micrometer on the sample plane and this focussing is monitored with a CCD camera mounted on a microscope objective and positioned across an opening in the platform and through the translucent sections of the samples. The samples used here were all bismuth thin films grown onto clean glass substrates using DC-sputtering technique with a bismuth target in argon. The film thickness was consistently measured to be of approximately 500 nm with a Dektak II profilometer, corresponding to a deposition time of 10 min, at a pressure of 22 mbar and a discharge power of 10 W.

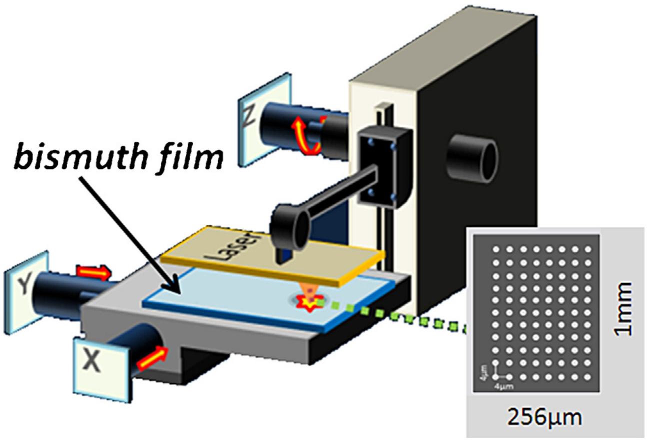

Fig. 1. Diagram of the laser platform used in this work. The control computer is not shown for clarity.

The bismuth films were then directly etched by the NIR laser without further preparation. A rapid characterization of the optimal lasing conditions under which the films may be ablated superficially helped determine that the power density that enabled surface modifications on the bismuth samples was 85 mW/cm^2 as measured with an optical powermeter. In this case, the resulting characteristic dimension of in-plane resolution was approximately 2–3 μm. Further experiments were then designed to etch a matrix of regular dots at different laser dwell times and pulse durations. The former is controlled via the scan velocity of the motorized translation stage while the latter is controlled by a custom-made electronic circuit precisely controlling the duration of the pulse [16]. Both times were monitored using a photomultiplier tube connected to an oscilloscope in order to discard any discrepancy between electronic control and actual shining durations. We made an important distinction between pulse and dwell times as the stepper motors may be displaced more or less rapidly between two positions and laser exposure; this may allow for more or less cooling time of the material, thus affecting the process in different ways (separation time between exposures and exposure time, respectively). To maintain boundaries between consecutive spots, these were etched each 4 μm, a greater separation than the aforementioned resolution. All experiments were performed in air, at atmospheric pressure and without any particular environmental control.

Finally, the characterization of the material after deposition and after the interaction with the laser was achieved with a scanning electron microscope (Jeol JSM6510 LV), a micro-Raman system (HR-800 LabRaman, Jobin-Yvon-Horiba) and atomic force microscope (Nanosurf Easyscan 2).

3. Results and discussion

3.1. Microbumps morphology

It is possible to see at a simple glance that white light is dispersed in the irradiated area of the layer due to the periodic microstructuring caused by the laser. This effect is observed in many natural examples of insect wings, material self-assembly, LIPSS structures or diffractive elements. The morphology of the bismuth films after the interaction between the laser beam and their surface has been studied to investigate its nature. The surface of the irradiated film is completely different to that of the initial film, as can be seen in Figs. 2–4. The result is the formation of small protrusions or microbumps that grow on the surface after the material is heated by the incidence of a single laser pulse. The heating of the material is high enough to melt the bismuth, considering the relatively low melting point of 271 °C and, following a process similar to what is described in [29], the material is rapidly cooled in a process of recrystallization or dewetting and is deposited again. However, the irradiated microscopic area of bismuth film is not precisely taking back its initial shape, but instead forms small clusters, which thickness and size depends on the irradiation parameters.

In our experiment, the power density was kept constant, although it has been reported that the micropatterns topology and size are strongly dependent on this parameter. As can be seen in Fig. 3, the laser defocusing caused by some non-planarity along one axis is clearly demonstrating that the beam power density at the