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FEM simulation of periodical local heating caused by Laser Interference Metallurgy

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ABSTRACT

Interfering laser beams of a high power pulse laser give the opportunity to apply a direct lateral interaction with metals based on mechanisms of photo-thermal interaction of features with a well-defined long-range order in the scale of typical microstructures (i.e., from the sub micrometer level up to micrometers). This study reports laser interference irradiation experiments on one- and two-layer thin metallic films. Depending on the energy of the laser beams different topographical regimes were observed and explained using thermal simulations. The transition of the topographical regimes could be explained due to local and periodical melting or vaporization of the layers. Measurements of the time-resolved electrical resistance of the films during laser irradiation were carried out and compared to the thermal simulations corroborating the experimental observations.

1. Introduction

The Laser Interference Metallurgy (Kim et al., 1995) is a technique that permits a local and periodic modification of the surface of materials. In this process, coherent laser beams interfere with each other on the sample surface, generating an interference pattern of energy (i.e., line- or dot-like patterns, depending on the configuration of the laser beams) with a well-defined lateral long-range order. This method already has been used successfully to fabricate periodic arrays on different types of materials as metals, semiconductors, and organic polymers (Ilcisin and Fedosejevs, 1987; Phillips et al., 1991; Heintze et al., 1994; Kelly et al., 1998; Nebel et al., 1998; Fukumura et al., 1998, 1994; Shoji and Kawata, 2000). Compared to the more common lithography methods, the novelty of Laser Interference Metallurgy lies in the direct processing of the probe itself rather than the exposure of a photoresist film.

In the case of metals, interference patterns produce a periodical heating through the local photo-thermal interaction mechanism (von Allmen and Blatter, 1995). Therefore the temperature can be increased in concentrated regions even over the boiling point.

Overlapping coherent and linear polarised laser beams produce interference patterns with a defined geometry that

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Table 1 – Samples configuration: material and thickness of each layer. In all cases glass was used as substrate

	Sample						
	A	B	C	D	E	F	G
1st layer	Fe(30 nm)	Cu(30 nm)	Ni(30 nm)	Fe(30 nm)	Ni(30 nm)	Cu(30 nm)	Fe(30 nm)
2nd layer	–	–	–	Al(30 nm)	Al(30 nm)	Al(30 nm)	Al(120 nm)

depends on the used wavelength and the angles between the beams. The two-dimensional line pattern produced by two laser beams has an intensity distribution described by:

$$I(x) = 2I_0 \cos(kx \sin\alpha)^2, \quad (1)$$

where I_0 is the intensity of one laser beam, λ the wavelength, α the angle between the beams, and k is the wave number:

$$k = \frac{2\pi}{\lambda}. \quad (2)$$

For this case, the period of the interference pattern is be given by:

$$d = \frac{\lambda}{2\sin(\alpha/2)}. \quad (3)$$

A three beam symmetrical configuration produces a two-dimensional dot-like pattern. Four planar beams interference realise a line pattern with thinner and higher peaks and thicker areas of low intensity compared to a two beam pattern.

In a previous work (Lasagni and Mücklich, 2005), the microstructure of several bi-layered metallic thin films was changed by laser interference irradiation using a line-type interference patterns (Eq. (1)).

In the case of bi-layered films where the metal with the higher melting point is placed on the top of the sample, two different topographical regimes were observed depending on the fluence of the laser (energy per unit area). For lower laser fluences, the molten material in the lower layer induces deformation over the upper layer obtaining a periodic pattern with out removal of material at the interference maxima positions. If the laser fluence is high enough to melt the upper layer as well, the latter is removed at the interference maxima obtaining a highly structured pattern.

Therefore, in order to properly understand this phenomenon, the calculation of the temperature profile as well as the quantities of molten and vaporized material as function of the laser fluence value must be considered. As result of the local heating, the electrical resistance of the films during the interference experiments is changed. Thus, the measurement of the voltage–time characteristic and its comparison with the thermal simulation can bring important information about the reliability of the simulation.

In this work, a thermal simulation by finite element method was carried out to calculate the molten- and vaporized regions of thin metallic films during laser interference irradiation. After that, the percentages of molten and vaporized metal were compared to the structure depth (height of the obtained periodical structures) of irradiated samples with one (Fe; Cu; Ni) and two metallic layers (Fe/Al; Cu/Al; Ni/Al). The thermal history of the simulation was compared with in situ time-resolved electrical resistance measurements during the laser interference experiments.

2. Experimental

The thin metallic films were produced by physical vapor deposition with an Ar-ion-gun sputtering facility (Roth & Rau, UniLab) on glass substrates (Marienfeld® soda-lime glass of hydrolytic class 3) under a vacuum of 10 Pa. The thickness of the films was monitored in situ using a microbalance (Tectra, MTM-10). In the case of the bi-layered samples, the metal with higher melting point was placed on the top of the sample. The thickness of the layers was varied obtaining the samples configuration shown in Table 1. For the laser interference irradiation experiments, a pulsed Nd:YAG laser with a wavelength of 266 nm, frequency of 10 Hz and pulse duration of 10 ns was employed. The primary laser beam was split into two beams to interfere with each other on the sample surface. An angle of 5.05° between the beams generates a line-like interference pattern with a period of 3.02 μm (Daniel et al., 2003). One pulse was chosen for each experiment. The laser fluence was changed from 0 to 250 mJ/cm^2.

The voltage–time evolution during the laser interference experiments was measured for the Fe/Al sample. For this propose, the Fe and Al layers were sputtered using a rectangle mask over a glass substrate obtaining 1 mm × 10 mm metallic films (see Fig. 1). A current source Keithley 2400 Digital Source Meter was employed to apply a constant current (16 mA) between the extremes of the metallic films. The voltage–time evolution was measured using a Digital Oscilloscope LeCroy

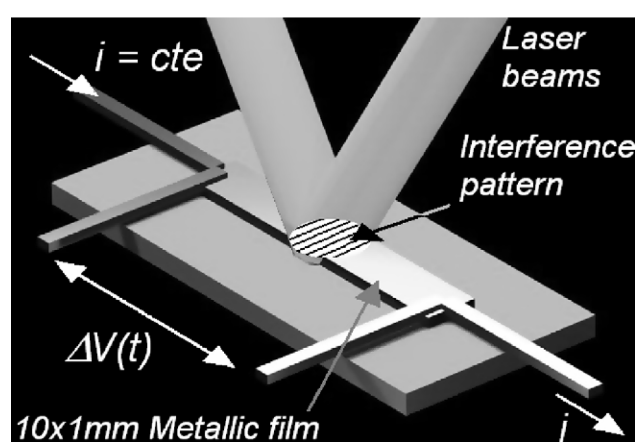

Fig. 1 – Experimental setup for the in situ time-resolved electrical resistance measurements. The characteristic ΔV(t) was measured with the oscilloscope. The constant current i was provided by the current source.