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The use of arc-erosion as a patterning technique for transparent conductive materials

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ABSTRACT

Within the framework of cost-effective patterning processes a novel technique that saves photolithographic processing steps, easily scalable to wide area production, is proposed. It consists of a tip-probe, which is biased with respect to a conductive substrate and slides on it, keeping contact with the material. The sliding tip leaves an insulating path (which currently is as narrow as 30 μm) across the material, which enables the drawing of tracks and pads electrically insulated from the surroundings. This ablation method, called arc-erosion, requires an experimental set up that had to be customized for this purpose and is described. Upon instrumental monitoring, a brief proposal of the physics below this process is also presented. As a result an optimal control of the patterning process has been acquired. The system has been used on different substrates, including indium tin oxide either on glass or on polyethylene terephtalate, as well as alloys like Au/Cr, and Al. The influence of conditions such as tip speed and applied voltage is discussed.

1. Introduction

In the past decade Organic Electronics has boosted the development of thin, transparent conductive oxide films, mainly of indium–tin oxide (ITO), either on rigid (glass) or flexible substrates. Currently Organic Electronics is facing the development of cost-effective manufacturing methods for mass production over large areas. Initiatives in this line have rendered attention to solution-processing techniques for the active organic layers [1,2] and to the use of flexible substrates. In this context, the process of creating electronic devices on a roll of flexible plastic, or roll-to-roll (R2R) technology, is considered the most promising solution for high-speed, large-area processing with great throughput. Jet-printing [3,4], nano-imprint lithography (NIL) [5], and laser ablation [6,7] are currently the most used patterning techniques compatible with a R2R setup.

Despite the progress made, the search of low-cost procedures for patterning is still open. In 1999 Hohnholz et al. [8] observed that stripes of an ITO coated glass could be partially removed by sliding a hard metal tip onto the ITO, while applying a moderate voltage (~15 V) between both, tip and substrate. The complete removal of ITO was subsequently achieved by wet etching in a 2 M hydrochloric bath for a few seconds. This technique was proposed as a simple method for the subdivision of ITO on glass substrates[9]. It should be noticed that ITO may be a very hard material [10] so that a simple mechanical scraping off is not suitable to electrically insulate two regions.

The authors attributed this effect to the high continuous current flow through the tip (~0.25 A) which presumably was able to locally heat the ITO up to the sublimation point during the tip motion. According to that assumption the authors performed some energy balance calculations in which the electrical energy supplied by the source ($E_{electric}$) was expressed in a continuous form $E_{electric} = (V^2/R_s) \times t$, where V is the bias voltage, R_s the series resistance between tip and ITO (estimated around 75 Ω), and t was a time factor deduced from the tip speed and size. This energy input was considered sufficient to overcome the heat dissipation effect as well as the different phase transitions (melting and boiling) to achieve a localized removal of the ITO layer. In any case, the authors did not monitor the current transient behavior, nor considered the crucial role of the internal bypass capacitor attached to the output of the power supply.

In this work we have performed controlled ablation of ITO and other metals using an experimental set up similar to that used by Holhholz et al. but customized for this purpose. We show evidences that the phenomenon observed in Refs. [8,9] was not due to a continuous supply of energy, but on the contrary, it results from a sequence of discharges involving huge transient currents of many amps. Hence this process is rather similar to that used in electrical discharge machining (EDM). EDM is widely used in industry for metal shaping. The working principle is based in the creation of arcs between the cutting electrode and the metal piece[11], by means of high voltage pulses. The sparks between both solids detach material from the metal piece, which is subsequently removed by a liquid or

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gas flux[12]. In this work we explain how is it possible to generate large discharges using continuous, low voltage sources.

In Section 2, the experimental set up to perform patterns on different conductive materials is described. Experimental evidences that permit us to explain the physical mechanism and thus, to control the patterning process are explained in Section 3. Conclusions are summarized in Section 4.

2. Experimental setup

A computer-assisted system (Fig. 1) consisting of an assembly of three micropositioners along the XYZ axis, has been developed. Motion along each axis is carried out by a high precision PLS-85 MICOS linear stage, provided with a 2-phase stepper motor and a closed loop system that improves accuracy. Resolution and repeatability down to 1 μm are guaranteed. The XYZ micropositioner is driven by a SMC-corvus-eco MICOS controller, connected to PC via RS-232 or USB interface, which is programmed with a specific software. Thus, the motion may follow a previously designed pattern. The maximum scanning speed allowed by our specific controller is 15 mm/s, and the working area comprises 10×10 cm^2.

A home-made mechanical head has been designed and adapted to the micropositioner. It is mounted on a methacrylate support to ensure its electrical insulation with the machine body. This piece includes a spring probe (marked by the yellow arrow in the picture) that enables upward and downward motions of the steel (or tungsten) needle, so different degrees of pressure may be exerted in contact with the sample. The probe metal type is not apparently a critical issue but since it works in contact mode, a hard metal is recommended when working with robust materials like ITO. Thus, the equipment behaves as a plotter, i.e., the pattern is designed with a vector-graphic design software, the resulting file is translated by the electronic controller, and the pattern is engraved on the sample.

The conducting tip is connected to a usual continuous power supply (2×30 V, 3 A) which constitutes a difference with respect to the pulsed voltage used in industrial electro-discharge machining. A home made circuit is connected in series to the needle with two purposes: on one hand, to bypass the internal 220 μF capacitor of the power supply substituting it by the desired external capacitors, and on the other hand, to ensure a fast charge and recharge of them.

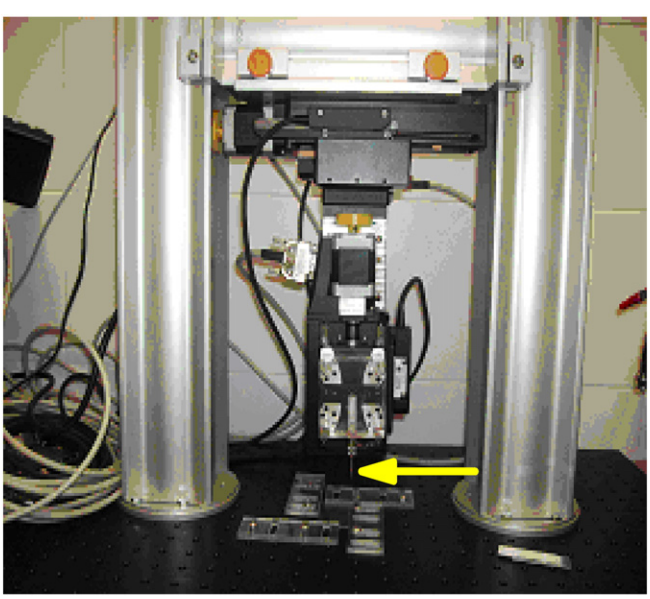

Fig. 1. Experimental set up for arc erosion patterning by means of a computer assisted XYZ micro-positioner. Yellow arrow marks the probe tip.

The voltages at the tip and at the external capacitor are monitored by a 200 MHz band-width oscilloscope during operation. Profiles of the performed grooves were measured using an Alpha-Step IQ contact profilometer by Tencor Instruments.

3. Results and discussion

When the tip comes into contact with the ITO substrate at a bias V = 0, the voltage may then be gradually increased up to tens of volts without creating any local damage, despite the high current (amps) injected into the material. In these conditions the tip slides without affecting the surface. However, if the tip is biased away from the surface at a suitable voltage of, e.g., 12 V, and then it approaches the ITO surface, a spark is generated at a sufficiently short distance, creating an insulated region around the tip and hence an open circuit. Despite the power supply is protected against short-circuits with a current limitation stage, the source includes an output bypass capacitor (around 220 μF) to filter high frequency signals. This capacitor is able to discharge at a very high current rate because it is directly connected to the low contact resistance.

Starting from this initial condition, the tip leaves a brown colored, insulated path as it slides onto the ITO surface. If the line depicts a closed loop, the inner region is insulated from the outer one by R > 2 Mohm. After a subsequent wet etching the residual ITO is removed achieving an open circuit between both regions.

In Fig. 2a, a plane view of the traces left on ITO by two different probes is shown. Both were performed under identical conditions, at a working voltage of 12 V. The inset in Fig. 2a shows the probe tips,

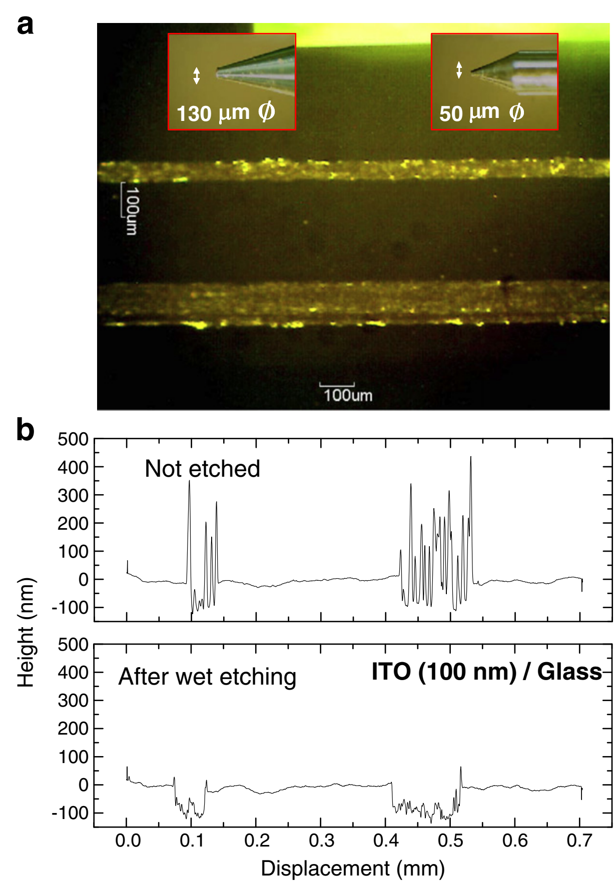

Fig. 2. (a) Optical micrograph of two stripes performed on ITO at 12 V, with different tips of 50 μm and 130 μm (see insets). (b) Cross section measured by contact profilometry showing the profile of the as-eroded layer (upper line) and after treatment in 6 M HCl acid for 10 s.