A comprehensive study of ion track enabled high aspect ratio microstructures in flexible circuit boards

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Abstract A process to form deep, vertical and high aspect ratio microstructures of solid as well as porous nature is presented. The process is capable of producing regions with perpendicular sub-micron metal wire connections, with a regulated effective metal density at numerous, arbitrarily specified locations. The structures are created in a two-metallic-layer polyimide laminate, i.e. a flexible printed circuit board. The high aspect ratio of the process is indebted to ion track technology. The laminate is irradiated with heavy ions creating a vertical damage anisotropy (individual ion tracks) in the polymer layer. Apertures in the front metallic layer define the geometry and the positions of the vertically projected structures. The tracks are selectively developed forming nanometer wide pores, which after prolonged etching grow in diameter and eventually merge creating fully opened cavities. Metallic structures have been replicated in these pores/cavities by electrodeposition of nickel and copper. We have fabricated open and dense clusters of separated micron or sub-micron sized wires as well as solid structures. Highly vertical, through hole microvias in average 39 μm wide, with a pitch of 100 μm have been fabricated. The smallest structures obtained were 25 × 25 μm square columns. The process appears promising for ultra-high density via batch production and has a strong potential of further miniaturising via dimensions.

1 Introduction

High aspect ratio microstructures is today of utterly importance in microelectronic and microsystem technology (MST). They are essential when thick layer or deep structures are required yet maintaining the microscopic lateral dimensions of the structures. The process described in this paper can be used to produce deep, vertical microstructures in polyimide based materials, used in e.g. flexible printed circuit boards (PCBs), a commercial electronic laminate material. The polyimide polymer has several beneficial properties, e.g. chemical resistance, temperature stability, favourable mechanical properties and a low dielectric constant. Partly because of this, it performs excellent together with standard silicon thin film lithographic processes. Apart from packaging and interconnection technology polyimide based flexible foils begin to find uses in microwave circuitry, porous biological membranes [1], gas separation and liquid filters, flat panel display technology, etc. Stacked polyimide and metal layers, i.e. flexible printed circuitboard materials have the potential of, in the same substrate, by hybrid integration of electronic- and integrated circuits (ICs) with above applications. The demands for high aspect ratio, deep structures accompany these new applications.

Today, flexible PCBs are used mainly for interconnection and packaging of integrated circuits. It is found in diverse consumer electronic products such as hard disks, cameras, and printers because of the extensive 3-D wiring capabilities, lightness and flexibility. Flexible PCB laminates consist of a stacked structure with one or several metallic layers (9–35 μm thick) with intermediate dielectric layers (25–75 μm). The flexible PCB material is elastic and can be bent and twisted to some extent, which is useful in an increasingly growing number of light applications where space or geometry is limited. The dielectric layer comes in several different forms; different polymer materials have been developed to resolve problems with e.g. humidity uptake and large dielectric constants.

Ion tracks offer unique possibilities for the realisation of nanometer-sized, high aspect ratio structures at low cost and high throughputs. Swift, heavy ions induce along their path a nanometric wide channel of transformed material, where each individual ion track may exhibit properties markedly different from the surrounding bulk material, [2, 3]. These tracks of distorted material are formed when thick or thin films of polymeric or other dielectric materials, are exposed to heavy ion irradiation with an adequate energy loss; for polyimide in the order of 0.5 keV/Å or more [4]. The length of the track may reach several hundreds of micrometers. Thus, extremely large aspect ratios can be realised. The tracks may be used directly, e.g. creating conducting and magnetic paths in dielectric matrices, or they may be selectively etched, i.e. transformed into pores [5].
Ion tracks may be irradiated at densities from one track per sample up to low \(10^{14}/\text{cm}^2\), where, in principle, all material is transformed. Most often densities in the \(10^8 - 10^{10}/\text{cm}^2\) region are used. Modern accelerators can produce in the order of at \(10^{12}\) tracks per second, which corresponds to a rate of 1 m²/s with a track density of \(10^9/\text{cm}^2\) (1 track per \(\mu\text{m}^2\)). The ion tracks are stochastically distributed across the sample surface with a certain ion track density, regulated by adjusting the irradiation time.

High ion tracks densities can be employed also for producing fully open cavities where the pores from etched ion tracks merge and form a trench, i.e. a fully etched volume. Arbitrary geometric shapes can be processed with this technique by utilising an etch-mask or irradiating through a stencil mask, we call this micromachining by ion track etching (MITE), [6]. Hence, the ion track irradiation process may express similarities with ion projection lithography (IPL) [7], and LIGA-like techniques [8], where a pattern is projected from a mask into a sensitive polymer. IPL can only be achieved in sensitive resists or polymers using a large ion density since each ion transfer less energy and no ion tracks are formed in the sample.

If the ion tracks are dissolved by selective wet etching it is today possible to make extreme high aspect ratio pores, e.g. in polycarbonate [9], used in their unrefined form in e.g. biofluidic filter applications or as templates for growing nanostructures, [10]. Polymer samples are normally etched in an alkaline or oxidising wet chemical agent. The severely damaged material in the ion tracks is then attacked preferentially. The tracks are quickly transformed into fine hollow channels, referred to as pores, which after prolonged etching widens laterally, [11]. In some materials, e.g. in polyimide [12], it is possible to control the geometry of the pores by changing etch conditions. The electrochemical processes and regimes associated with electrodeposition in nanoporous templates have been studied extensively [13].

Much progress has been made in producing and studying narrow magnetic nanowires grown in ion track membranes, [14, 15]. Of special interest have been magnetic nanowires built up from multilayers of alternating magnetic and nonmagnetic materials, which are being studied for high-density magnetic reading and storage devices, [16]. Giant magnetoresistive (GMR) and spin valve structures can be produced this way. Also, with respect to flexible PCBs we should mention the magnetically tuneable microwave filters using electromagnetic resonance of magnetic nanowires in the dielectric between a microstrip transmission line and its ground plane, [17, 18].

Today, there are only a limited number of commercial products produced by ion track technology. Low-dose irradiated polymer foils are used as filters in water purification, analytical membranes in biomedicine and chemical pollution studies, and as cell cultivating membranes. The superior properties of ion track membranes for these applications are mainly based on the well-defined size and geometry of the pores.

Presently, in our research we have, by combining ion track techniques with microlithography, addressed the technical need to control patch sizes and nanowire array dimensions, allowing more advanced structures. The ion tracks induce an etchable vertical damage anisotropy in the dielectric. When merging the cluster of pores and electroplating we can also create plated through holes or vias.

In this paper we demonstrate a batch production process technique to create ultra-small via interconnections in polyimide based flexible PCBs, which can be used to create copper wire vias in solenoid and toroidal coils as well as magnetic circuits based on sub-micron nickel wires. We also present a model of the lateral area/perimeter roughness of structures taking into account the stochastically nature of the ion tracks distribution.

We have previously shown [19], that ion irradiation gives a statistical distribution of the individual ion tracks (the number of tracks is Poisson distributed inside a specific area). However, using precisely defined (by lithography) via apertures in combination with large numbers of ion tracks (subsequently transformed into metal wires) enables the production of vias with metal cross-sections of less statistical spread than ordinary processed vias.

2 Fabrication process

The combination of ion track techniques (irradiation and development) and microlithography/electrodeposition processes are here exploited for the fabrication of deep vertical structures that couples to double-sided interconnection layers. Process details are listed in Table 1.

The structures have been realised in a flexible PCB composed of a stacked structure with two copper layers laminated on the respective side of a dielectric layer. Foils without any intermediate adhesive layers and with relatively thin copper layers were acquired. Before ion irradiation, the copper layers are thinned down to a thickness of only 3 to 5 \(\mu\text{m}\). This enhances the range, i.e. the penetration depth, of the ions in the underneath polyimide layer. In addition, the resolution of the subsequent copper layer lithography is improved.

Below follows the required process steps, the section paragraphs are referring to Fig. 1.

(a) A cyclotron accelerator equipped with a raster x-y scanned ion beam (scanned area \(60 \times 60\) mm, using a 1 mm step) was utilised to irradiate the laminated flexible foils (area \(44 \times 44\) mm) with swift heavy ions across the full surface, with uniform intensity, Fig. 2. The ion-beam spot diameter is in average 9.3 ± 1.8 mm (standard deviation). Highly parallel tracks with a divergence of less than 0.1° are produced by the accelerator set-up used.

(b) After irradiation, openings defining the vias and structures are machined in the copper layers, exposing the underneath polyimide layer. Double-sided photolithography with a liquid spin resist in combination with subtractive isotropic wet etching of the copper is used.

(c) The surrounding copper forms an etch-mask, resistant to the highly aggressive, warm, alkaline and oxidising etch solution used for opening the ion tracks. The etch rates (bulk and track), can be adjusted by changing the pH of the etch solution [12]. Etching was performed and studied for two different pH, 9.9 and 11.5. Etching