Proton Beam Writing: A New 3D Nanolithographic Technique

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1 Introduction

Current microelectronics production technologies are essentially two-dimensional (2D), and are well suited for the 2D topologies prevalent in microelectronics. As semiconductor devices are scaled down in size, and coupled with the integration of moving parts on a chip, there is expected to be a rising demand for smaller micro-electromechanical systems (MEMS) and nanoelectromechanical (NEMS) devices. High aspect ratio three-dimensional (3D) microstructures with nanometer details are also of growing interest for optoelectronic devices. Therefore it is essential to develop new lithographic techniques suitable for the production of high aspect ratio 3D micro- and nanocomponents. Proton-beam (p-beam) writing at the nanometer level is being developed at the Centre for Ion Beam Applications (CIBA), National University of Singapore, and has been shown to be a promising new 3D lithographic technique [1, 2]. In 2005 p-beam writing was incorporated in the Japanese road map for 3D nanofabrication [3]. Many other institutes have recently also started to look at p-beam writing, but mainly at the micron level. P-beam writing is a new technique that utilizes a focused beam of fast (MeV) protons written directly into a resist to produce a 3D latent image in a resist material (e.g., for sub-100 nm lithography, PMMA, SU-8, or HSQ). P-beam writing is the only technique that offers the capability of direct-write high aspect ratio nano- and microstructures. The secondary electrons induced by the primary proton beam have low energy and therefore limited range, resulting in minimal proximity effects. Low proximity effects coupled with the straight trajectory and high penetration of the proton beam enables the production of 3D micro- and nanostructures with well-defined smooth side walls. The current status of p-beam writing will be discussed. Recent tests have shown this technique capable of writing high aspect ratio walls up to 160 and details down to 20 nm in width with sub-3 nm edge smoothness [1, 4]. Computer simulations have

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confirmed minimal proximity effects in p-beam writing [5]. These features make p-beam writing a direct write technique of high potential for the production of high aspect ratio structures with sub-100 nm detail in the lateral directions for rapid prototyping. In combination with electroplating, p-beam writing can fabricate precise 3D metallic moulds and stamps for batch and high-volume production, using either nanoimprinting or soft imprint lithography. Potential applications will be discussed in Boxes 10, 11, 12 and 13.

P-beam writing is a new technology with no commercial instruments available as yet. Technical and commercial development of p-beam writing have been hampered by the difficulties encountered in focusing MeV ions to sub-100 nm dimensions. These difficulties have recently been overcome [6] and the first prototype p-beam writer has recently been constructed at CIBA [7].

2 Design of a Proton Beam Writing System

2.1 P-Beam Exposure Station

In the early stage, p-beam writing was performed using a belt driven Van de Graaff accelerator (HVEC AN 2500). This type of accelerator in general exhibits poor energy stability, and consequently produces proton beams with wide intensity fluctuations (typically in the tens of Hz frequency range). Therefore, in order to achieve accurate exposure doses, a beam normalization procedure has to be developed: see Sect. 2.2. Initially p-beam writing was performed using the Oxford Microbeams OM2000 end station in a nonoptimized setup. Typical feature sizes that can be obtained with this kind of setup are down to the submicron level. More details about the setup used in CIBA in combination with the HVEC AN2500 Van de Graaff accelerator can be found in [8–11]. There are several other groups around the world active in p-beam writing with either a Van de Graaf accelerator or a Pelletron type of accelerator [12–16]. Some groups are doing masked proton beam lithography with MeV protons [17] or keV protons [18–20].

Recently several groups started to use cascade accelerators for p-beam writing [6, 21–24]. In Table 1 a summary is given of the activities of different groups in developing p-beam writing. Only with the cascade accelerators have people come close to the 100 nm level. Most of the systems used are not dedicated p-beam writing systems. In CIBA the first dedicated system for p-beam writing has been developed and has achieved 22 nm p-beam written features and spot sizes down to $35 \times 75\ \mathrm{nm}^2$.

In the rest of this chapter the CIBA system will be discussed, since it is currently the only system capable of routinely writing deep sub-100 nm features using MeV protons.

In 2000 a 3.5 MV HVEE Singletron$^{\mathrm{TM}}$ accelerator was installed in CIBA. P-beam writing with this accelerator can routinely achieve spot sizes at the sub-100 nm level because of its high brightness and increased beam stability. In addition a new nuclear nanoprobe facility has been developed at CIBA [6, 7]; see Fig. 1. This facility is the first of its kind dedicated to p-beam writing on a micro- as well as on a nanoscale.