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Nuclear Instruments and Methods in Physics Research B 241 (2005) 346–350
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Field emitter arrays and displays produced by ion tracking lithography

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Available online 2 November 2005

Abstract

When ions of sufficient electronic energy loss traverse a dielectric film or foil, they alter the chemical bonding along their nominally straight path within the material. A suitable etchant can quickly dissolve these so-called latent tracks leaving holes of small diameter (~10 nm) but long length – several microns. Continuing the etching process gradually increases the diameter reproducibly and uniformly. The trackable medium can be applied as a uniform film onto large substrates. The small, monodisperse holes produced by this track etching can be used in conjunction with additional thin film processing to create functional structures attached to the substrate. For example, Lawrence Livermore National Laboratory and Candescent Technologies Corporation (CTC) co-developed a process to make arrays of gated field emitters (~100 nm diameter electron guns) for CTC's Thin CRT™ displays, which have been fabricated to diagonal dimensions >13 in. Additional technological applications of ion tracking lithography will be briefly covered.
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Keywords: Electronic stopping; Ion track; Field emitter; Latent track; Nanotechnology; Flat panel display

1. Introduction

For more than a half dozen years, Lawrence Livermore National Laboratory and Candescent Technologies (formerly Silicon Video Corporation) engaged in a partnership to develop field emitter array flat panel displays, FED. As the effort progressed to ever larger substrates, the various processes such as deposition and etch that are used in the fabrication steps were transferred from ones initially developed at LLNL, see [1], for small substrates to Candescent's facility in San Jose for large substrates. The largest substrate size employed was 320×340 mm. Eventually, all processes, even high-energy ion tracking, could be performed at CTC with commercially produced tools. The beam line and associated large end

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0168-583X/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.nimb.2005.07.243

station at LLNL accepts substrates up to 40 in. in diagonal (100 cm). The accelerator system consists of a 4 MV single ended National Electrostatics Corporation Pellatron, bending magnet, x–y rastering, dosimetry system and shutter.

2. Field emitters display technology

We briefly review the steps involved to build gated field emitter arrays, the active device in a FED. For an introduction to field emitters and vacuum microelectronics, the reader is directed to *Vacuum Microelectronics*, edited by Wei Zhu [2]. The completed FED is shown in Fig. 1. To begin the process, a large substrate is patterned with rows and columns of metal. Each intersection of a row and column will eventually define a subpixel – i.e. one of three colors (red, green, or blue). The rows are insulated from the columns by a ~100 nm thick silicon dioxide layer. At each subpixel, a thousand field emitter structures will be located. Fig. 2 shows the process in cross section to form the field emitters. Energetic ions are directed through the top layer of polycarbonate. Each ion breaks the bonds in the polymer along its straight line trajectory. This chemical change in the polymerization of the polycarbonate

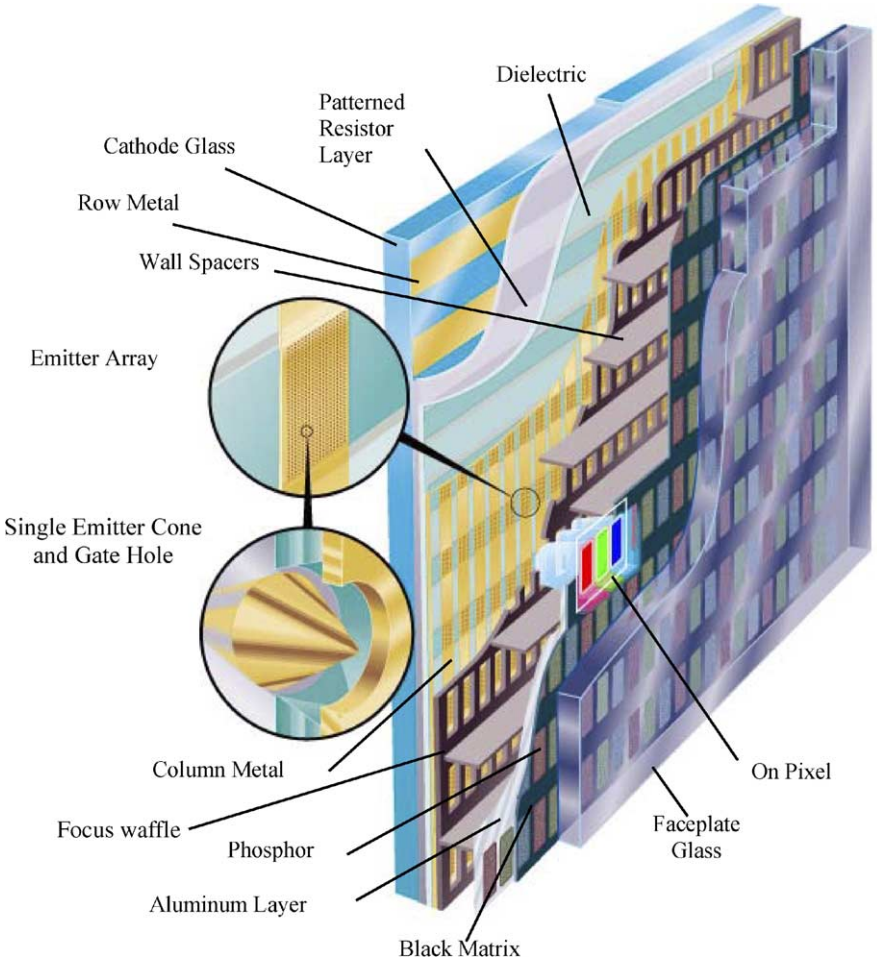


Fig. 1. Exploded view of field emitter display. Five inch and 13 in. prototypes have been fabricated.

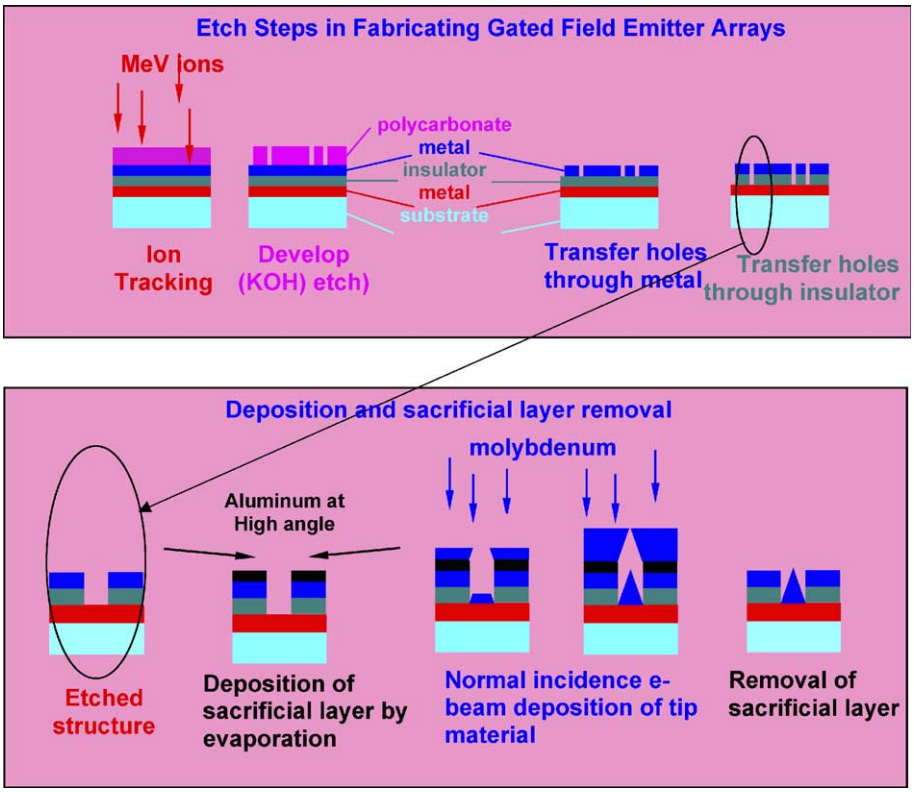


Fig. 2. Process steps to form field emitter arrays using ion tracking lithography.

drastically alters the chemistry of the material. A suitable solution (6 molar potassium hydroxide, KOH) quickly removes the altered material from each latent ion track. By continuing the etch process, the hole diameter is increased uniformly and precisely, now at a much slower rate since the material is unaltered polycarbonate. When the desired hole size is achieved, the etching of the polycarbonate layer is halted. For the CTC process, the diameter was set at 120 nm.

The holes formed in the polycarbonate can now be used as a mask for plasma etching of the chrome gate metal. Any remaining polycarbonate surviving this process can be removed by dissolving in acetone. The chrome film, with holes, is used as the mask in the formation of the cavity in the underlying dielectric by anisotropic reactive ion etching using a CHF_3/O_2 gas mixture. A subsequent isotropic liquid etch using 6:1 buffered HF for 60 s opens the cavity further in order to prevent unwanted electrical properties that would occur during the Spindt deposition steps [3] and briefly described below.

The first deposition step creates a thin parting layer of aluminum (typically 10 nm) on top of the chromium film. By performing this evaporative deposition at grazing incidence, the bottom of the cavity remains free of aluminum. The second deposition step is performed at normal incidence using e-beam evaporation of molybdenum. As the deposition continues, the gate hole slowly closes. This has the effect of gradually reducing the area deposited into the cavity – thereby forming a cone that is self-aligned with the gate opening. Once the cone is complete – the parting layer can be removed – releasing also the molybdenum deposited onto it, yet leaving the cones of molybdenum firmly attached to the row metal film. The current geometry uses gate holes that are 120 nm in diameter and cones 100 nm high.

These dimensions are three times smaller than reported in the earlier work [1].

In the FED, the array is placed under vacuum and to turn on a pixel, each molybdenum cone is biased negatively and the surrounding gate, positively. The electric field concentration at the tip is large enough to induce field emission – quantum mechanical tunneling of electrons from the bulk into the vacuum region. In the Candescent device, a focussing waffle is employed to accurately direct the electrons to the inside of the face plate which is coated with phosphor materials (red, green, blue) used in ordinary CRT displays. The gap between the face plate and the emitter array is 1.2 mm and, during operation, the phosphor is biased at 7 kV. Because of the small size and sharpness of the tips produced, only 10 V is needed to switch a pixel element. Brightness control is achieved by the length of time the pixel is turned on and is therefore conveniently controlled digitally.

The $5\frac{1}{2}$ in. display uses the QVGA format. The pixel pitch is 0.37 mm, the brightness is 600 Cd/m^2 and the contrast ratio is 500:1. The power consumption is 2 W. Thirteen inch diagonal displays have also been fabricated and the technology is scalable to much larger areas. In addition to twice the power efficiency of liquid crystal displays, the technology offers wide viewing angle and operation at extreme temperatures (hot or cold) and no color changes when pressure is applied to the front or back surfaces by, for example, a stylus or finger. Lifetime is 50,000 h, limited by the phosphor, and adequate for most applications [4].

3. Other examples of ion tracking lithography

Ion tracking lithography can produce structures as small as 20 nm in diameter or as large as 100 μm. Ion tracking has also been shown to lead to cylindrical holes in thin films of thermal fused silica [5], which affords a stronger mask material than polycarbonate and other options.

Fig. 3 shows an example of a simpler structure produced in the early stages of the CTC/LLNL collaboration. This ''bed of nails'' structure is produced by electroplating into the etched ion tracks. The left panel is a view of the edge of the specimen created by fracturing the substrate. The polycarbonate host has been forcibly ripped off of the ''nails'' near the fracture yet they remain firmly attached to the substrate and are evidently

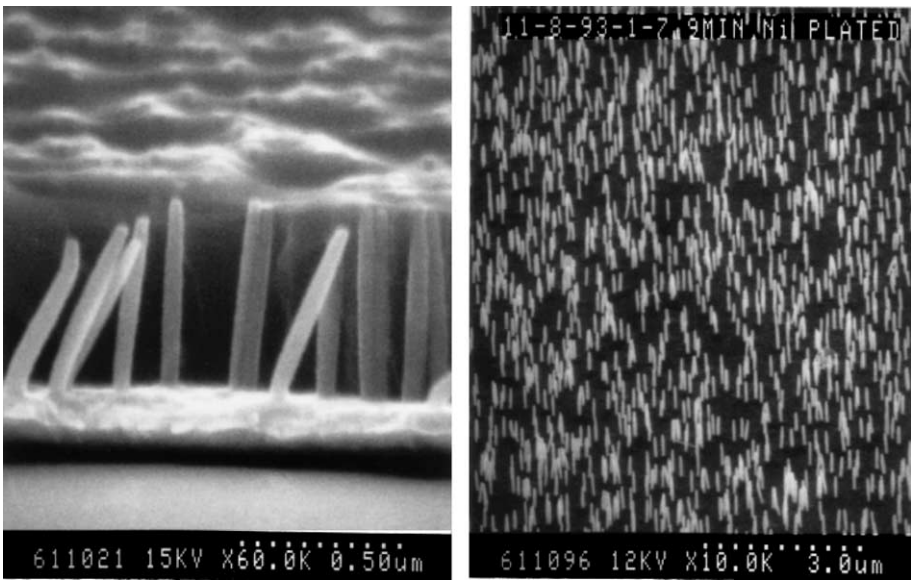


Fig. 3. ''Bed of nails'' produced by electrodeposition of nickel into ion tracks etched in polycarbonate. Left: edge view of fractured substrate reveals the ''nails'' to be firmly attached and malleable. Right: angled surface view after removal of the polycarbonate.

malleable. In the right panel, the polycarbonate host has been removed over the entire area shown. Note the uniformity in the diameter, 80 nm and height, 600 nm, of the nails. The high field emission from such structures gave the team early encouragement to develop the low voltage, gated field emitter device.

The bed of nails structure can be used as a basis for more complicated devices and structures. The technique offers excellent control of important parameters and is amenable to a large number of metals, semimetals and semiconductors. Moreover, by switching the solution or the electrochemical potential, different layers can be deposited.

4. Conclusions

Ion tracking lithography has become a viable manufacturing tool for making monodisperse holes in suitable media such as free standing or deposited thin films of polycarbonate or glass. The hole diameter can be set accurately to any desired size in the range of 20 nm (or less) to several microns by control of the etch conditions. The length of the hole is established by the thickness of the film from tens of nanometers to tens of microns. Although the holes are randomly spaced, the average density can be controlled at the percent level by dosimetry techniques and are governed by simple Poisson statistics. Once the holes are formed, additional processes can be utilized such as, selective etch, electrochemical, chemical vapor, or physical deposition. A host of these processes is employed in the fabrication of field emitter arrays. Current substrates allow for 13 in. diagonal displays, but much larger substrates appear feasible.

Acknowledgements

The development of field emitter displays involved on the order of twenty people at LLNL and even more at Candescent. Among the more significant contributors at LLNL are Alan Jankowski, Jeff Morse and Robert Contolini. Among the large group at Candescent, T.S. Fahlen, John Macaulay, Lawrence Pan, Jack Porter and Chris Spindt, come immediately to mind. Peter Searson at Johns Hopkins is also gratefully acknowledged for early etch and electro-deposition studies. This work was performed under the auspices of the US Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract no. W-7405-Eng-48.

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