Progress in Field Emitter Sources for Digital Electrostatic E-beam Array Lithography*

L.R. Baylor, D.H. Lowndes, V. I. Merkulov, G. Eres, D.B. Geohegan, J.E. Hardy, D.L. Hutchinson,
A. A. Puretzky, M. Simpson, C.E. Thomas, J.B. Wilgen, J.H. Whealton, E. Voelkl
Oak Ridge National Laboratory

Electron beam technology is a strong candidate for patterning the generations of lithographically produced semiconductor devices that apparently are beyond the reach of optical lithography, i.e. with line widths 70 nm and smaller. However, writing with a single electron beam is slow and therefore expensive. The digital electrostatic e-beam array lithography (DEAL) concept proposes writing simultaneously with millions of electron beams in a massively parallel and easily programmable field emitter array. The concept is also scalable to produce line widths up to an order of magnitude smaller (10 nm or less). Because DEAL is maskless it is expected to be much less expensive than several competing technologies. Using DEAL, an entire 300 mm wafer, with 40 nm pixels, could be written in 30 seconds (including line-edge control down to 1-nm using gray-scale exposure).

Field emitter arrays (FEA's) are two-dimensional assemblies of miniature cathodes used as electron beam sources. A custom-made digitally addressable field emitter array (DAFEA) with built-in electrostatic lenses is proposed for direct writing of lithographic patterns on resist-coated semiconductor wafers, as shown schematically in Fig. 1. Each emitter cathode is individually addressable, thus enabling patterns to be programmed into the DAFEA before being written onto the target wafer. The entire array can be turned "off" by switching the bias grid from positive to negative. However, when the bias grid is "on" (biased positive), those pixels with the emitter biased negative relative to the grid will emit. The bias grid metallic layer, separated from the cathodes by an insulator (nominally SiO_2), will have relatively small capacitance. Using a modest power supply the DAFEA can then be biased with a low positive or negative voltage, with switching times on the order of a microsecond or less, to turn the writing current on and off.

In addition to rapidly writing large areas, this concept has the great economic advantage of using a digitally programmable "virtual mask", which can be re-programmed electronically for new layers within milliseconds. No actual physical mask is required—the technology is maskless.

Key to the entire concept is a reliable stable solid-state emitter that can be lithographically placed on 200 nm cathodes. Demagnification of 5 to 20 then results in 40 nm to 10 nm write beams. Progress during the past year as well as ongoing research at ORNL to develop carbon-based emitters, primarily using vertically aligned carbon nanofibers (VA-CNFs), will be presented. Completely deterministic patterned growth of multi-walled VA-CNFs has been achieved at low temperatures (~700°C) at ORNL, as shown in Figs. 2 and 3. Field emission measurements reveal that these VA-CNFs are good field emitters, with emission threshold fields as low as 12 V/micron. The emission also is spatially uniform over large areas of relatively sparse CNF forests. VA-CNFs display stable emission for more than 144 hours (and still counting) of continuous 100nA operation at 10^{-6} torr vacuum conditions. This corresponds to more than one year of operation at the proposed 1% duty cycle.

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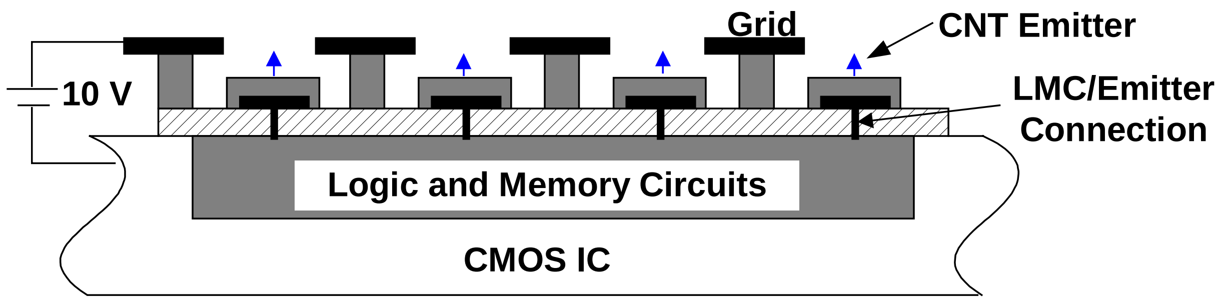

Figure 1: Schematic of a DEAL source device. The Logic and Memory Circuits (LMCs) include current-source circuitry.

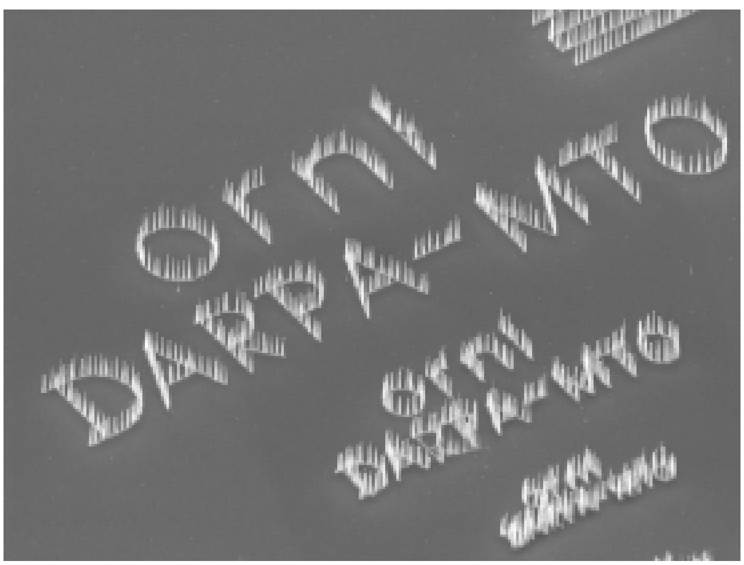

Figure 2: Deterministically patterned lines of vertical carbon nanofibers. Lines are approximately 500nm in width. (Submitted for publication in *Applied Physics Letters*)

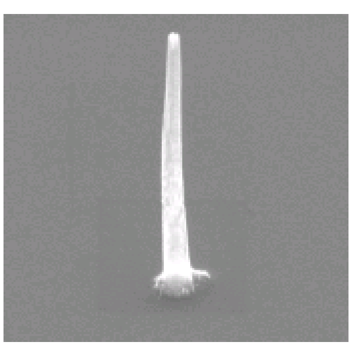

Figure 3: Isolated multi-walled vertical carbon nanofiber (CNF) produced by lithographically etching the catalyst. This example is about 200nm at the base and 100nm at the tip. (Submitted for publication in *Applied Physics Letters*)