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Miniaturization Techniques for Accelerators

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Abstract

The possibility of laser driven accelerators[1] suggests the need for new structures based on micromachining and integrated circuit technology because of the comparable scales. Thus, we are exploring fully integrated structures including sources, optics (for both light and particle) and acceleration in a common format – an accelerator-on-chip (AOC). Tests suggest a number of preferred materials and techniques but no technical or fundamental roadblocks at scales of order 1μm or larger.

INTRODUCTION

The exponential growth in the complexity of high energy accelerators and colliders dictates techniques that leverage infrastructures such as those being developed for optical telecommunications (MEMS) and integrated circuit electronics (SOC). Acceptable materials (and wavelengths) must allow velocity synchronism between many laser and electron pulses with optimal efficiency in high radiation and intense laser fields.

Tests related to deep etching, fabrication and radiation damage on candidate amorphous and crystalline materials shows Si to be ideal from 1.2-10 μm but other candidates exist[2]. We have made micro-planar electron optics and wigglers on Si capable of pulsed currents of >1 A without failures and etched micro structures in Si having aspect ratios on a wall's height-to-thickness of 500:1 with surfaces that were flat, parallel and smooth to <10 nm. Also, we have made optical structures such as gratings and matrices of pyramidal structures for field emission and alignment at different μm level scales.

Representative examples are discussed to suggest that there are IC analogs for essentially *all* particle and light sources as well as their respective optics. To date, we have found no technical nor fundamental roadblocks to building such integrated systems on scales consistent with infrared lasers. The need for many parallel beams of both light and particle implies useful applications in other fields.

Still, many questions remain that need answering when even the circuit board equivalent seems beyond reach but this is roughly equivalent to the terawatt table top laser (T^3) and SLAC linac that was used to do photon acceleration by electron beams[3] – the inverse process. Now, everyone takes the T^3 laser for granted. Thus, our goal is to show the possibility of an AOC by showing that it is consistent, or not inconsistent, with microelectronic/photonic integration technologies that should provide incredible leverage.

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GENERAL TYPES OF STRUCTURES

In many regions, the mean directions of both laser and particle will be the same. In such cases, it is then useful to impose an axis or plane of symmetry i.e. cylindrical or planar structures. In either case, tensor beams are possible[4] although they appear easier to implement in a multiplanar form. For several reasons, we will consider only planar structures below.

Within this class, several possibilities can be considered for integrated systems including: 1) In-Plane, 2) Out-of-Plane, 3) 3-Dimensional and hybrids such as 4) Multi-Planar as opposed to typical, off-chip, discrete components. Types 1), 2) and 3) are *single* wafer structures with 1) and 2) distinguished by the number of fab steps required to get more than one active layer whereas 3) can have true 3D open structures. For OP type, we include structures made on top of other structures or ones fabricated on opposite faces of a wafer but still planar or ones using layer transfers to a single wafer. MP includes the possibility of more than one wafer e.g. stacked, OP wafers requiring precise alignment with high relative placement accuracy.

Basic Examples

We have made many etching tests to verify and understand previous work and to extend it to our applications. Our masks usually include several structures over a range of scales to test different etchant and mask conditions. While it is usually possible to visually discriminate out-

Figure 1: A 500 μm period grating etched on (100) Si.

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comes with an SEM, it is difficult to capture good photos of the smaller, deeper feature sizes, e.g., 5-20 μm slits in a 500 μm thick wafer. We note that the fastest to slowest etch directions in Si are [211], [110], [100] and [111].

Reflective and Diffractive Optics elements (DOE) are wavefront transformers that can *replace* or improve (via some hybrid form) classical optical elements. Of interest is the use of reticulated steps (binary optic approximation) to correct both spatial and color aberrations in lenses or any optical system. Fig. 1 shows a large period (d=500 μm) grating with mirror surfaces, etched to a depth of $\sim$290 μm along the (111) planes of a (100) Si wafer. The edge angle with the top surface is 54.6°. This grating is intended for reflective optics but has many refractive-diffractive uses.

In refractive mode, for monochromatic light below the bandgap, arrays of beamlets can be produced with angles, relative to the incident beam, and relative separation from one another calculable from:

$$m\lambda = d\ sin(\theta_m)\ . \tag{1}$$

m is the order. Our source example[4, 5] uses two DOEs.

With decreasing d, angles increase and for d$<\lambda$, an AR surface superior to AR coatings can be generated using such patterns with differing index. An array of line sources (Fig. 1) or points (Fig. 2) are practical since subwavelength binary features < 50 nm have been produced.

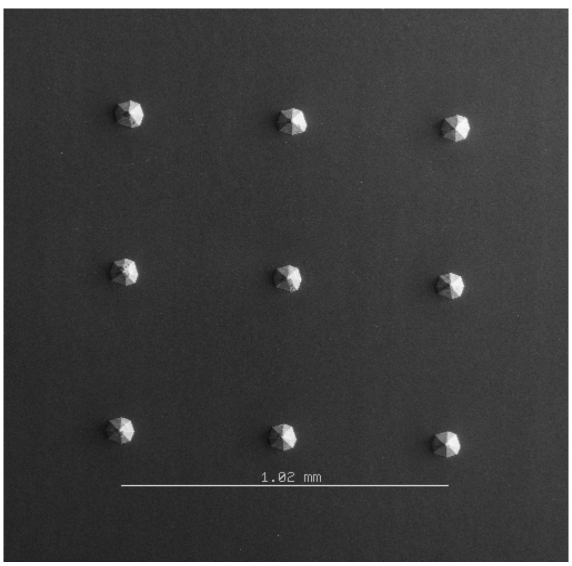

Figure 2: A 500 μm period matrix etched on (100) Si[6].

Planar Undulators and Optics for particles exist for all of the above structure types and it is straightforward to write down coil-dominated fields for their many physical expressions. The hardest aspect is to assemble and measure their fields without a test beam. Using gold, many undulator patterns were produced on both quartz and Si wafers. By scaling the line width and length for 20, 50 and 100 μm periods they have the same resistance R and have been driven with 1 ns pulse currents up to several amps without failure by conditioning to higher currents while carefully monitoring and constraining R. To accommodate particle beams, periodic trenches and slits are needed that can also be used as pattern generators. An important question is whether they can be made deep enough to accommodate a true tensor beam structure. In Fig. 3 we demonstrate the possibility of etching a single, thick wafer **or** stack to give accurate registration between wafers. IR light does not provide sufficient resolution.

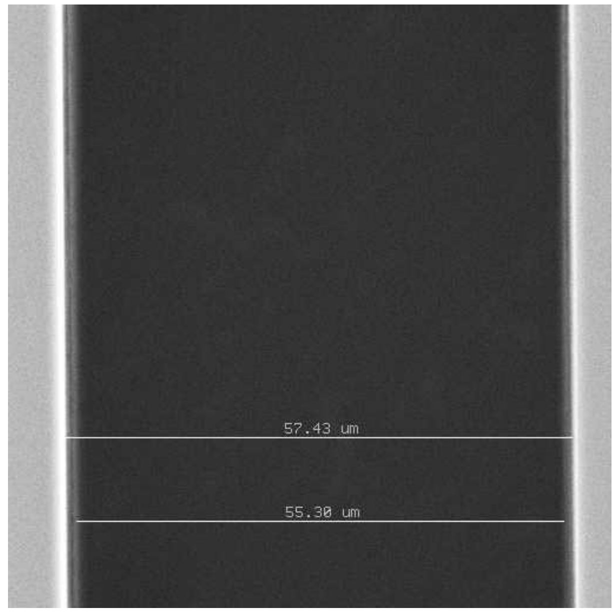

Figure 3: View of a 50 μm slit etched along the [111] lines in a 500 μm thick, (110) Si wafer. The wall height-to-thickness ratio is 500:1. Thinner slit widths are harder to view and thicker ones have worse resolution.

In this and similar SEM pictures, we showed that it is possible to go from an unknown [111] orientation on a (110) wafer to make small accurate slits with length-to-width ratios of 250:1 and wall height-to-width ratios of 500:1. We also demonstrated that the surface of the walls were flat, parallel and smooth to better than $\approx$10 nm by finding and focusing on particles < 100 nm in size on the wall surfaces. Although we have achieved 15-2000 μm slits on one wafer with a single etch it is clear that at least two or more etching steps are needed for such cases.

High Q Examples

Solenoids/Helical Undulators are difficult elements. Most standard electronic components are in-plane but some components such as the inductors used in VCOs could be improved (Q, parasitic effects, etc.) by 3D versions. Today, pancake coils are used whose axis is perpendicular to the wafer surface. By requiring some form of in-plane coil e.g. a spiral, both area and feature size are increased inefficiently because the line width only needs to be a few μm (skin depth at 1 GHz)[7]. Such coils also drive the field into the material which increases the frequency dependent impedance via eddy currents through the substrate and other nearby impedances. Improvements are clearly possible. Chua et al.[8] developed a 3D coil with a higher Q by balancing compressive and tensile stress in lithographically defined, deposited material. This demonstrates a direct IC analog for the solenoid in magnetic optics and by extension the helical undulator.

Microcavity, Optical Resonators are one of the more important optical systems one needs to integrate with other photonic components. The laser AOC itself is a resonator but needs to integrate an active medium with other such elements. The semiconductor diode is one example while spherical or ellipsoidal “microspheres” are another.

The Alignment Problem

For perspective, Si transmits only IR light >1.1 μm for normal incidence[2] which is not adequate for wafer-to-wafer matching or aligning top-bottom masks. Wafer flats and notches are often rounded to improve breakage but quoted accuracy of $\pm 1^\circ$ is a problem. Improvements in the original boule x-ray measurement and transfer with optical polishing of the flats is possible since the original batches undergo good control and labeling.

Tensor Source and Laser Driver

For conventional radio frequency accelerators, the rf gun was a major improvement that was well matched to the rf accelerator. Increasing rf frequency improves things because it allows higher gradients that increase the inertial resistance to space charge blowup out of the cathode as well as helps to avoid bunching systems. However, if a buncher is required, for laser based frequencies employing conventional rf guns, then space charge debunching and transverse blowup appears difficult to avoid. This remains true even when the microbunch charge is considerably reduced. Thus, laser acceleration schemes require new source techniques compatible with the wavelength regime.

A generic drive laser system is suggested in Fig. 4 where the laser depends on the system to be driven. It could be used, in various forms, to drive a pin-cushion cathode to produce tensor beams or as a power source for the accelerator where Ti:Sa, Er:YAG and Cr:ZnSe are possible candidates. Notice that several elements in this Fig. 4 could be DOEs in trenched Si or Silica.

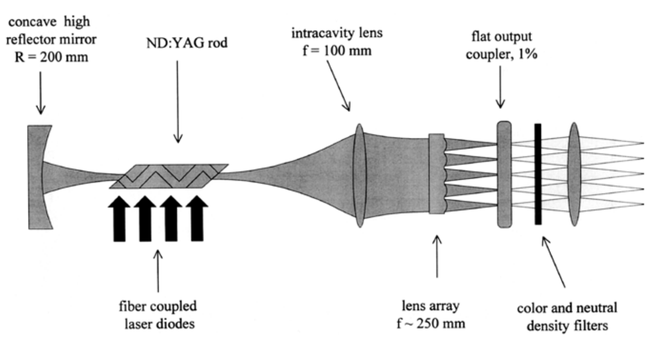

Figure 4: Laser driver for multibunch source & accelerator.

Fig. 5 shows a gun illuminated from the output of Fig. 4. Tips may not be necessary for some materials such as GaAs and this may well be advisable for stability and lifetime but these characteristics depend on the applied voltages, wavelengths and intensities. Polarized beams can be generated using circularly polarized light. STM probes produce about 4 pA/V of ballistic electrons from GaAs with no laser light in a technique called ballistic electron emission.

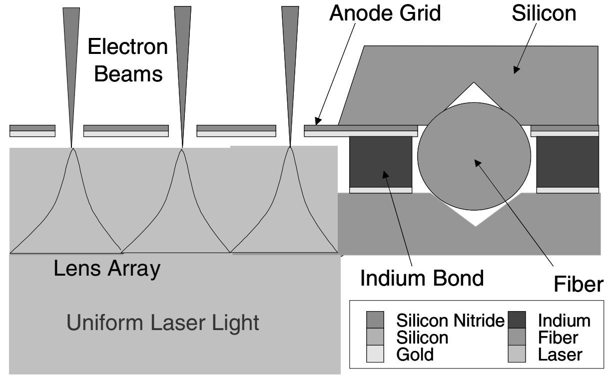

Figure 5: Schematic for a backlit, gated photocathode[5].

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[5] J.E. Spencer, “The Silicon Lattice Accelerator”, to be published in *Intl. J. Mod. Phys.*.

[6] One might expect a four sided pyrimidal structure but 8, as shown here, and 16 was discussed in Neil A. Cade et al., *IEEE Trans. Elect. Dev.* 36(1989)2709. A sharper, possibly more acceptable, tip is possible using (110) wafers and coating.

[7] This is clearly inadequate for many applications such as optical computers. Semiconductor lasers have operated at rates > 1 THz. At 29 GHz, several pJ pulse energies in ps pulses have been demonstrated: Krainer et al., “29 GHz modelocked miniature Nd:YVO_4 laser”, *Elect. Lett.* 35(1999)1160.

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