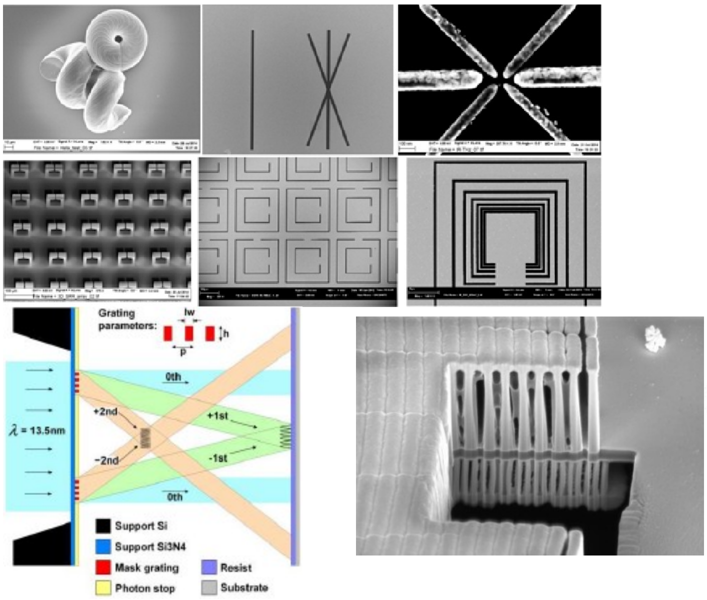

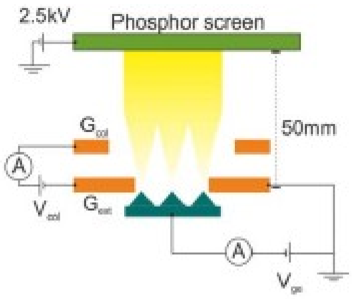

SLS Symposium on

Nanostructures

Tuesday, May 5, 2015

10:00 to 12:15, WBGB/019

10:00 Field enhancement of THz light using nano-antennas
Salvatore Bagiante

10:30 Double-sided Fresnel zone plates
Istvan Mohacsi, I. Vartiainen, M. Guizar-Sicairos, P. Karvinen, V. A. Guzenko, E. Müller, E. Färm, M. Ritala, C. Kewish, A. Somogyi and C. David

11:00 Coffee

11:15 Development of low-emittance field emission cathode: An all-metal stacked double-gate nanotip array
Pratyush Das Kanungo, C. Lee and S. Tsujino

11:45 Ultra-dense and large area sub-10 nm silicon nanowires using extreme UV interference lithography
Daniel Fan, Hans Sigg, Ralph Spolenak, Yasin Ekinci

Field enhancement of THz light using nano-antennas

Salvatore Bagiante, PSI-LMN, Linear and Nonlinear THz Science

In recent years there has been great progress in the exploration of the electromagnetic spectrum between 0.1 and 10 THz, also known as the THz gap. This region gives access to many interesting physical properties of semiconductors, molecular crystals, ferroelectrics, gas molecules, superconductors and biological objects, whose spectroscopic signatures are largely to be discovered in the THz range. Today the generation of THz pulses with sufficiently high peak electric fields is still rather limited, mostly due to technological constrictions. Diffraction limited focusing can be overcome by using suitable metallic structures. These structures which act as antennas, efficiently collect the incident THz radiation and concentrate it in a small volume thus enhancing the THz field inside the gap. Nano-antennas open new scenarios for the use of cheap and conventional tabletop setup for all those experiments where high field strength is needed.

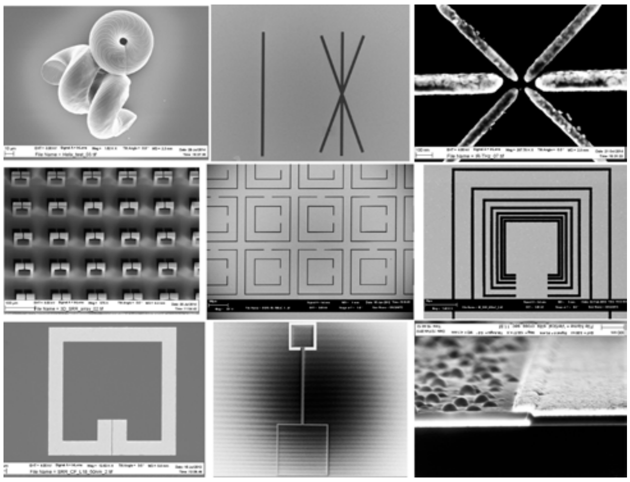

Fig. 1 Collage of different THz antennas featuring with nanometer sized gaps.

Double-sided Fresnel zone plates

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Abstract

The stacking of Fresnel zone plates is a known method for the production of highly efficient zone plate optics [1]. However, positioning of the zone plates requires a mechanical setup or permanent gluing to keep their alignment within a fraction of the smallest zone width. We present a novel approach for the production of double sided zone plates by patterning both the front and the back side of the same support membrane to significantly increase the efficiency. The two zone plates on the same membrane provide the same benefits as stacked zone plates, but in an easy to use monolithic form.

Patterning two identical high resolution zone plates on the same membrane allows us to double the effective structure height to produce better diffraction efficiency at high photon energies. We combined this with the zone doubling technique [2], by patterning two HSQ resist templates on the membrane and coating it with Iridium to produce double sided zone plates with 30 nm smallest zone width and 1.1 micron combined structure height (Fig. 1.). Focusing efficiencies up to 9.9% were measured at 9 keV with diffraction limited focal spots.

Since the focusing efficiency of binary Fresnel zone plates is fundamentally limited, multilevel phase shift profiles are required to produce efficiencies beyond 40% [3]. Such multilevel profiles can be produced by stacking of two binary zone plates [4]. Therefore we patterned a “coarse” binary zone plate with π phase shift and a double density “fine” zone plate with π/2 phase shift to produce an effective four step phase shift profile (Fig. 2.) with 200 nm smallest zone width. The tested zone plates provided up to 54.7% focusing efficiency at 6.2 keV.

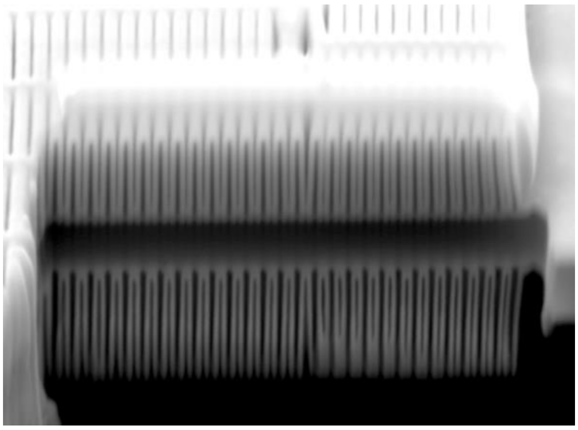

Figure 1: FIB cross section of a double-sided line-doubled zone plate with 30 nm zone width and 1.1 µm combined structure height.

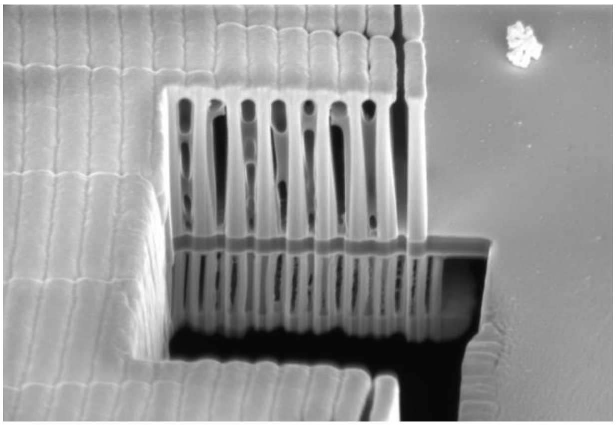

Figure 2: FIB cross section of a double-sided blazed zone plate. The coarse structures are on the front and the dense are on the back side.

References

[1] J. Maser et al., “Near-field stacking of zone plates in the x-ray range”, Proceedings of SPIE Vol. **4783**, 74-81(2002)
[2] J. Vila-Comamala et al., "Ultra-high resolution zone-doubled diffractive X-ray optics for the multi-keV regime", Optics Express **19**, 175-184 (2011)
[3] E. Di Fabrizio et al., "High-efficiency multilevel zone plates for keV X-rays", Nature **401**, 895-898 (1999)
[4] S. Chen et al., "Absolute efficiency measurement of high-performance zone plates", Proceedings of SPIE Vol. **74480D** (2009)

Development of low-emittance field emission cathode: An all-metal stacked double-gate nanotip array

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Field emission cathodes are known to have extremely high beam brightness and large transverse coherent length when used as a single-tip emitter. However they emit a limited total current. Although a field emitter array cathode with several hundreds to millions of nanotip emitters in parallel can generate ampere level current [1, 2] a large angular divergence of individual beamlet in the order of ~30 degrees results in the large transverse beam temperature of ~10 eV, a fact that makes them unsuitable for high current and high brightness applications such as the THz vacuum electronic amplifiers etc. Noting that intrinsic transverse temperature of field emission beam is in the order of tens of meV, double-gate devices equipped with on-chip electron extraction gate electrode and the second gate electrode for individual beam collimation, see Figure 1, have been proposed some time ago, but actual devices suffered from the quenching of the emission current upon application of the negative, collimation potential, that was only recently surmounted. The PSI-type double-gate FEAs with the large collimation gate aperture, Figure 1, is one of those that is compatible with the high acceleration potential of tens of MV/m, a prerequisite for the high-brightness and accelerator applications.[3, 4]

Here we present recent experiment on the characteristics of electrically generated electron beam of double-gate FEAs demonstrating an order of magnitude reduction of the transverse velocity spread of an array of 4×10^4-tip devices. After careful conditioning of the FEA in UHV and in Ne-gas environment it led to the total un-collimated current in the order of a few 100 µA. Ne conditioning improved both the homogeneity and intensity of the beam (see Fig. 2(a)). Collimation characteristics at gate voltages V_{ge} of 67, 90 and 100V was compared by plotting the rms beam radius against the collimation ratio k_{col}, between the extraction and collimation voltage in Fig. 2(b). For all three cases the rms radius decreased from 4-6 mm at k_{col} = 0 to ~0.6 mm at k_{col} = 1. The estimated transverse velocity spread evaluated from the beam image exhibited a 125-fold decrease which is a significant improvement from the value reported in our earlier work [2]. Comparison was also made with a single double-gate tip device that showed similar collimation characteristics as the FEA. In addition, we will also discuss a recent measurement of the transverse beam emittance using a DC gun test stand that confirms the previous low energy results.

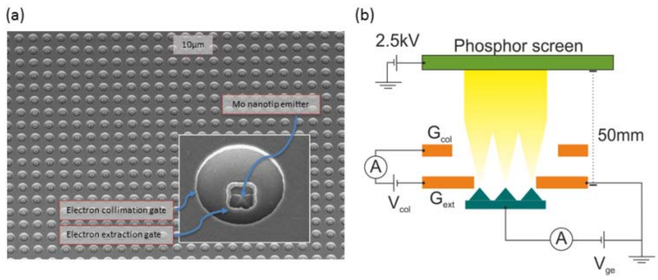

Fig. 1 (a) SEM image of an FEA with 10µm pitch. The inset shows a single device consisting of the Mo tip emitter, the extraction and the collimation gate. (b) Schematic view of the electron beam collimation experiment. Electron extraction potential V_{ge} (> 0) and the beam collimation potential V_{col} (< 0) are applied at the same time to generate the collimated field emission beam. The phosphor screen potential Van was 2.5 kV.

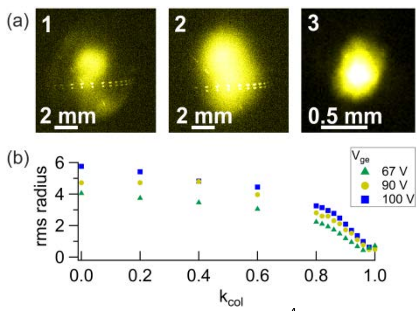

Fig. 2 (a) Field emission microscope images from a 4×10^4-tip device at a V_{ge} of 67 V – 1) and 2) uncollimated, under UHV and after Ne conditioning respectively, 3) after Ne conditioning and fully collimated. (b) Variation of the emiss current and the rms beam radius with the increase of k_{col} for V_{ge} between 67 and 100 V.

References

1. A. A. Fomani, S. A. Guerrera, L. F. V. Garcia and A. I. Akinwande, IEEE Trans. Electron Devices 61, 2538 (2014).
2. D. Whaley, R. Duggal, C. Armstrong, C. Bellew, C. Holland and C. Spindt, IEEE Trans. Electron Devices 56, 896 (2009).
3. P. Helfenstein, V. A. Guzenko, H.-W. Fink and S. Tsujino, J. Appl. Phys. 113, 043306 (2013).
4. P. Das Kanungo, P. Helfenstein, V. A. Guzenko, C. Lee and S. Tsujino, J. Vac. Sci. Technol., B, 33, 03C113 (2015,).

Ultra-dense and large area sub-10 nm silicon nanowires using extreme UV interference lithography

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Optical lithography has been the backbone of semiconductor device manufacturing for the past 50 years, due to its high throughput, yield, and scalability. As feature sizes shrink and device density increases, as predicted and guided by Moore's Law, new optical lithography methods are needed to increase the resolution [1]. In parallel, much research has focused on grown nanowires of a few nm in diameter which exhibit size effects in their physical properties. Currently, optical patterning approaches such as multiple patterning and DUV immersion are reaching their technological and physical limits. One candidate to replace these methods is patterning at the extreme ultraviolet (EUV) wavelength of 13.5 nm.

Lithographic pattern resolution is ultimately limited by the wavelength of light used. By decreasing the wavelength down to 13.5 nm, the theoretical patterning limit becomes 3.4 nm. Using EUV light, the XIL-II beam-line at the Swiss Light Source, Paul Scherrer Institut, is able to pattern features down to 7 nm half-pitch [2]. Spatially coherent light with 4% bandwidth from a synchrotron undulator source is incident upon a transmission mask. The mask is composed of diffraction gratings made of metal or inorganic photoresist and a zeroth order photon stop, supported on a silicon nitride membrane. The diffracted beams from the mask then interfere to produce a sinusoidal areal image which can then be recorded in photoresist [3].

The patterning resolution is restricted by the diffraction mask resolution. However, some advantages of this method include very large depth of focus up to 10 mm, very high throughput (10 s per exposure), large area patterning up to 5 x 5 mm^2, and absence of proximity effect in contrast with electron beam lithography. It is also highly reproducible with good quality and is therefore suitable for industrial operation as well as enabling research to prepare the industry for production of the next generation of semiconductor devices.

$$p = \frac{\lambda}{2\sin(\theta)} = \frac{g}{2m}$$

g: grating period
m:diffraction order

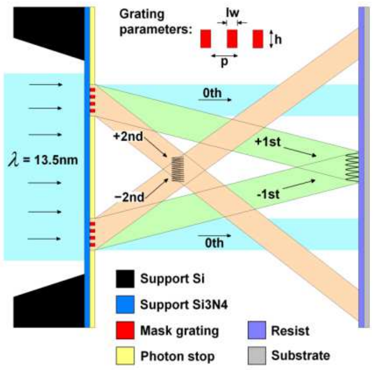

Figure 1. Schematic of EUV-IL. The mask gratings diffract the incident light into beams which interfere, with periodicity, p, given by the equation above. The interference pattern is recorded in resist on wafer.

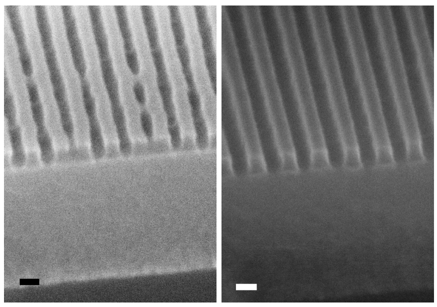

Figure 2. Cross-sectional SEM images of silicon nanowires etched into silicon-on-insulator substrate using RIE-ICP. Scale bar is 20 nm. Left: 14 nm half-pitch. Right: 16 nm half-pitch.

References

[1] International Technology Roadmap for Semiconductors 2013 report. http://www.itrs.net/Links/2013ITRS/Home2013.htm [Online], accessed 19/10/2014.

[2] B. Päivänranta, A. Langner, E. Kirk, C. David, Y. Ekinci, "Sub-10 nm patterning using EUV interference lithography," Nanotechnology, vol 22, 375302, 2011.

[3] N. Mojarad, D. Fan, J. Gobrecht, Y. Ekinci, "Broadband interference lithography at extreme ultraviolet and soft x-ray wavelengths," Opt. Lett., vol 39, pp.2286-2289, 2014.