Fabrication of mm-Wave Undulator Cavities using Deep X-ray Lithography

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The possibility of fabricating mm-wave radio frequency cavities (100-300 GHz) using deep x-ray lithography (DXRL) is being investigated. The fabrication process includes manufacture of precision x-ray masks, exposure of positive resist by x-ray through the mask, resist development, and electroforming of the final microstructure. Highly precise, two-dimensional features can be machined onto wafers using DXRL. Major challenges are: fabrication of the wafers into three-dimensional rf structures; alignment and overlay accuracy of structures; adhesion of the PMMA on the copper substrate; and selection of a developer to obtain high resolution. Rectangular cavity geometry is best suited to this fabrication technique. A 30- or 84-cell 108-GHz mm-wave structure can serve as an electromagnetic undulator. A mm-wave undulator, which will be discussed later, may have special features compared to the conventional undulator. First harmonic undulator radiation at 5.2 KeV would be possible using the Advanced Photon Source (APS) linac system, which provides a low-emittance electron beam by using an rf thermionic gun with an energy as high as 750-MeV. More detailed rf simulation, heat extraction analysis, beam dynamics using a mm-wave structure, and measurements on 10x larger scale models can be found in these proceedings.[1]

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I. INTRODUCTION

A mm-wave undulator uses a time-varying electromagnetic field instead of a static, periodic magnetic field to produce coherent synchrotron radiation.[2] When relativistic electron beam traveling in an rf or mm-wave EM field is subjected to transverse forces, a coherent radiation can be generated that is quasi-monochromatic, similar to that from the conventional undulator of the permanent magnet type. The mm-wave undulator can support smaller undulator periods (typically 1-mm or less) and has faster tuning ability which is achieved by changing the frequency of operation.

The new micromachining technology, known as the LIGA process (LIGA is a German acronym for Lithographe, Galvanoformung, and Abformung), was first demonstrated by W. Ehrfeld and co-workers.[3] High aspect ratio machining, using x-ray lithography, etching, and plating techniques, have developed to the degree that sub-millimeter actuators, motors, gears, etc. can be built with great accuracy. Electric field levels as high as 50 MV/m and magnetic field levels of 1 T have been achieved with components. The idea of applying these techniques to develop rf cavities for mm-wave linacs,[4] undulators,[5] free electron lasers,[6] and mm-wave amplifiers started at Argonne National Laboratory in 1992.

The DXRL process allows the manufacture of very precise features, on the order of submicrons, in wafers in a two-dimensional plane with perpendicular walls of a few millimeters depth and virtually no run out. To make the three-dimensional structure required for the mm-wave undulator, one must be able to mount and bond two wafers together with an accuracy of better than a few microns, build meter-long structures with similar accuracy that also provide channels for vacuum pumping, adequate cooling, and focusing elements for beam dynamics. Major challenges of the DXRL techniques are: fabrication of the wafers into three-dimensional rf structures; alignment and overlay accuracy of the structures; adhesion of the PMMA on the copper substrate; and selection of a developer to obtain high resolution. Efforts have been directed towards meeting these challenges.

II. MM-WAVE UNDULATOR

As an example of the DXRL-fabricated cavity, a mm-wave undulator was designed. The basic mechanism of the mm-wave undulator is similar to the conventional undulator of the permanent magnet type, and the equivalent magnetic field of the mm-wave undulator is given by:

$$B_{eq} = \left(1 + \frac{Z_0}{Z_w}\right)\frac{E_0}{c} \approx \frac{2E_0}{c} \ ,$$

where Z_0 is the free-space wave impedance (377 Ω), Z_w is the waveguide impedance of the traveling wave, c is the speed of light, and E_0 is the transverse electric field of the standing wave. Its undulator period is given as follows:

$$\lambda_u = \frac{\lambda\lambda_g}{\lambda + \lambda_g} \ ,$$

where λ and λ_g are free-space wavelength and guide wavelength, respectively.

The muffin-tin type mm-wave undulator is shown in Fig. 1. It consists of 30-cell rectangular cavities with dimensions of 714 μm long, 2032 μm wide, and 780 μm deep; two input couplers; and matched cavities at both ends. The rf parameters of the undulator are given in Table I. The undulator parameters are shown in Table II.

The Advanced Photon Source (APS) linac system can provide a low-emittance electron beam up to 750 MeV using an rf thermionic gun that improves the emittance by a factor of at least 10 over the conventional triode geometry DC gun. With the future APS linac system upgrade, one can take advantage of the mm-wave undulator, since its period is much smaller than the conventional undulator. The synchrotron radiation from the full-scale muffin-tin mm-wave undulator has been calculated and the results for the first

TABLE I. The rf parameters of the muffin-tin mm-wave undulator.

Frequency	f	108 GHz
Shunt Impedance	R	312 MΩ/m
Quality Factor	Q	2160
Group Velocity	v_g	0.043c
Attenuation Factor	α	13.5 m^{-1}
Accel. Gradient	E	10 MV/m
Peak Power	P	29.1 kW

TABLE II. The undulator parameters with the APS linac /rf gun.

Charge Particle Beam Energy	E_o	650 - 750 MeV
Average beam current	I	1 mA
Deflection Factor	k_u	0.0467
Equivalent Magnetic Field	B_{eq}	0.33 Tesla
Undulator Wavelength	λ_u	1.0 mm
Number of Periods	N	80
Length	l	8 cm
Gap Height	g	0.6 cm

harmonics are shown in Fig. 2. With beam energies of 650 MeV to 750 MeV and average beam current of 1 mA, the first harmonics of the undulator radiation are at 4.0 keV and 5.2 keV, respectively.[7]

The nominal dimensions of a single cavity are on the order of 1 mm or less with a 0.1% machining precision with the DXRL technology. Two wafers are aligned over one another using alignment and bonding techniques developed for micromachined electron microscopes.[8] Alignment grooves are machined into the wafer at the same time the other cavity features are being machined. Precision glass fibers are placed into the grooves and bonded and clamped in place. As example, the features of a sub-centimeter, scanning electron microscope fabricated by this technique are shown in Fig. 3. In the mm-wave undulator, coolant flows across the top and bottom of the structure, which is not shown in Fig. 1, since only a 2-dimensional view is shown in the figure. Vacuum pumping is provided through slots in the horizontal plane of the structure. The dimensions of the slots are chosen to be below cutoff of the operating frequency, but large enough to allow higher-order modes (HOMs) to leak out of the structure into a damping structure.

III. FABRICATION

The simplified version of the DXRL process is shown in Fig. 4. It consists of making a x-ray mask, preparing a sample and x-ray exposure, developing, and electroplating the structure. In DXRL, the requirements imposed on the resist materials, resist coating process, and development are much different from the thin resist layers. No dissolution of unexposed positive resist is allowed during development and good adhesion of the high-aspect ratio resists structure to the copper substrate is essential. In addition, the microstructures must have high mechanical stability and low internal stresses to prevent stress corrosion during exposure and development. Also, the resist material must be compatible with the electroplating process.

DXRL with hard synchrotron radiation allows resists up to 1000 μm thick to be fabricated with sub-micron accuracy. A high-accuracy DXRL mask was constructed through an intermediate mask, using a soft x-ray lithography step at the Center for X-ray Lithography in Stoughton, WI (1-GeV Aladdin machine). A plating base of Ti/Au 75/300

Å was used for the e-beam writer and then 3μm Au was plated on the intermediate mask. For the DXRL mask, 25-μm Au was plated over a 200-μm Si wafer where the x-ray was exposed and removed. To observe the high depth-to-width aspect ratio in the final product, micron range structures were patterned on the DXRL mask.

PMMA, which was either a 1-mm-thick sheet or was cast to a copper substrate, was used as a positive resist. The copper substrate was diamond-finished to have a flatness of 5 μm over 2 inches, and then either an oxide film was grown less than micron thick or an equally thick Ti coating was deposited in order to promote better adhesion to the copper substrate. When the PMMA film was cast onto the copper substrate, it was then annealed at various temperatures 110 - 170 ^{o} C for one to three hours.[9] Initially, the ALS beamline (Advanced Light Source at Berkeley) was used to perform the x-ray exposure, but it required excessive time to expose the sample of 1-mm-thick PMMA (typically more than 20 hours). Later, the NSLS (National Synchrotron Light Source) beamline X-26C was used to expose the sample. The transmitted x-ray intensity was calculated, based on the NSLS bending magnet parameters, and is plotted in Fig. 5. The ratio of the top dose to the bottom dose for the 1-mm-thick PMMA, is about 1.5. During the exposure, the sample was enclosed in a He-purged housing with Kapton window, and the sample holder baseplate was water-cooled.

Two different developers were used in the developing process. The first developer[10] was a mixture of 60 % vol 2-(2-butoxy-ethoxy) ethanol, 20 % tetrahydro-1, 4-oxazine, 5 % 2-aminoethanol-1, and 15 % DI water. The allowed dose range was 1.6 to about 20 kJ/cm^3. Below the threshold the crosslinked resist could not be dissolved, and above this range damage to the resist can occur from production of gases in the PMMA. The second developer was methyl-iso-butyl ketone (MIBK) diluted with 2-propanol. After developing the microstructure, copper can be electroplated to the positive resist and the surface can be diamond-finished. We haven't yet reached this stage of the electroplating program.

IV. SUMMARY AND FUTURE WORK

The 1-μm alignment accuracy and sub-micron machining accuracy of the 30-cell mm-wave undulator cavity still requires optimization of the PMMA development process and successful electroplating into narrow structures.

Rf measurements and high power tests will be required after the prototype of the 30/84-cell mm-wave undulator structures are fabricated with the DXRL technology. The goal will be to test the undulator cavities with the APS linac beamline to characterize the synchrotron radiation generated from the mm-wave undulator. We plan to continue to develop the technology using the beamline at the APS Sector 2 bending magnet.[11] The beamline, to be installed sometime in 1996, will be dedicated to DXRL for microstructure fabrication, and will consist of a 500-μm Be-window (25 H and 50 V mm^2 expose area), various filters for low-energy cut-off, and a Pt mirror for thermal load reduction and high energy cut-off. Use of the APS Sector 2 bending magnet will reduce x-ray exposure time to about 20 minutes.

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Fig. 1. The 30-cell, $2\pi/3$ mode, 108-GHz mm-wave undulator.

Fig. 2. Synchrotron radiation from the 80-cell mm-wave undulator.

Fig. 3. Alignment technique, used to build the sub-centimeter SEM.

Fig. 4. Simplified DXRL process.

Fig. 5. Transmitted x-ray intensity during PMMA exposures for DXRL at NSLS, energy (eV) vs. intensity (watt/cm^3).

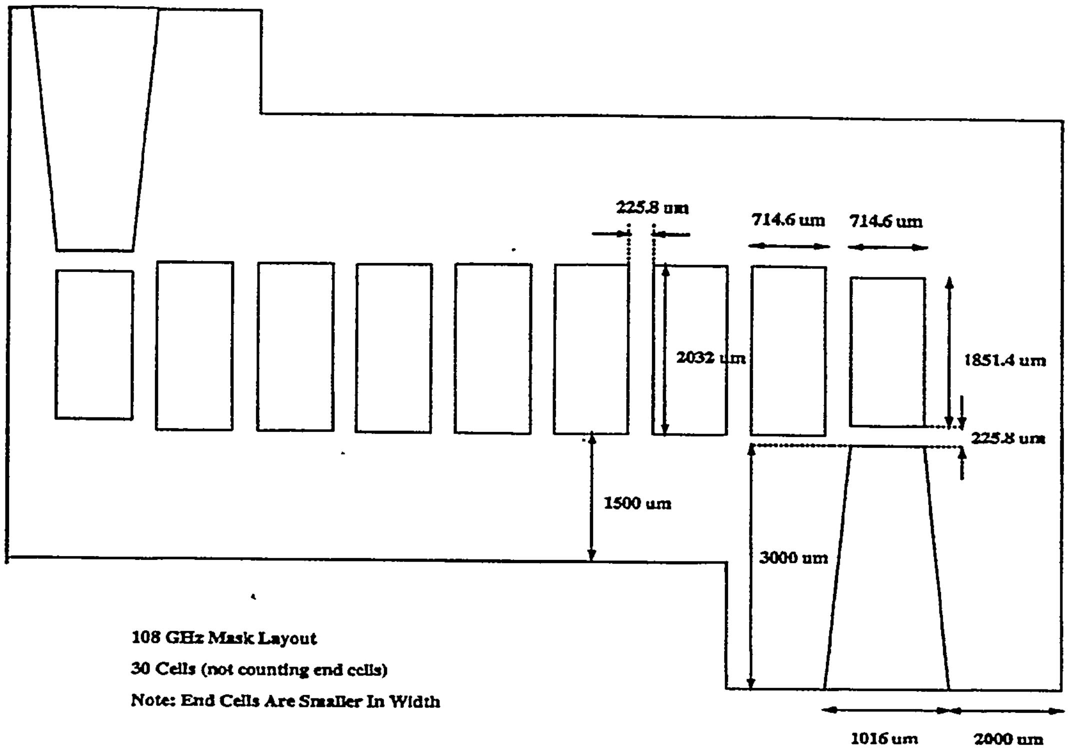
225.8 um
714.6 um
714.6 um
2032 um
1851.4 um
225.8 um
1500 um
3000 um
108 GHz Mask Layout
30 Cells (not counting end cells)
Note: End Cells Are Smaller In Width
1016 um
2000 um

Fig. 1.

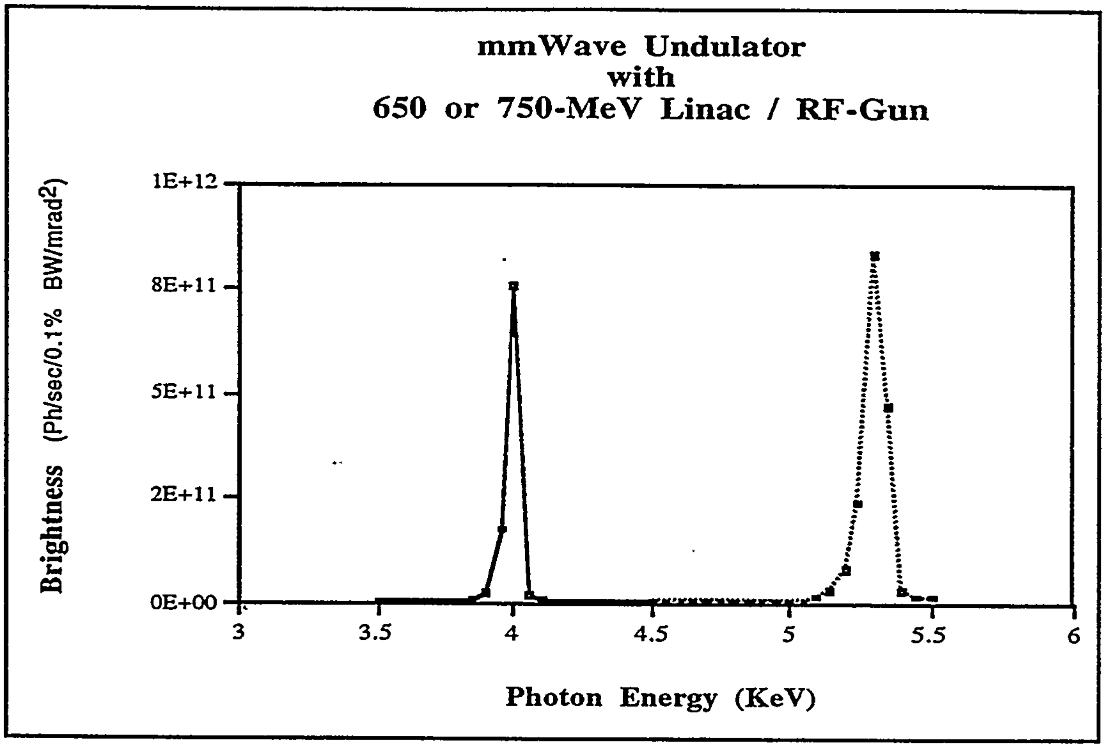
mmWave Undulator
with
650 or 750-MeV Linac / RF-Gun
1E+12
8E+11
5E+11
2E+11
0E+00
Brightness (Ph/sec/0.1% BW/mrad2)
3
3.5
4
4.5
5
5.5
6
Photon Energy (KeV)

Fig. 2.

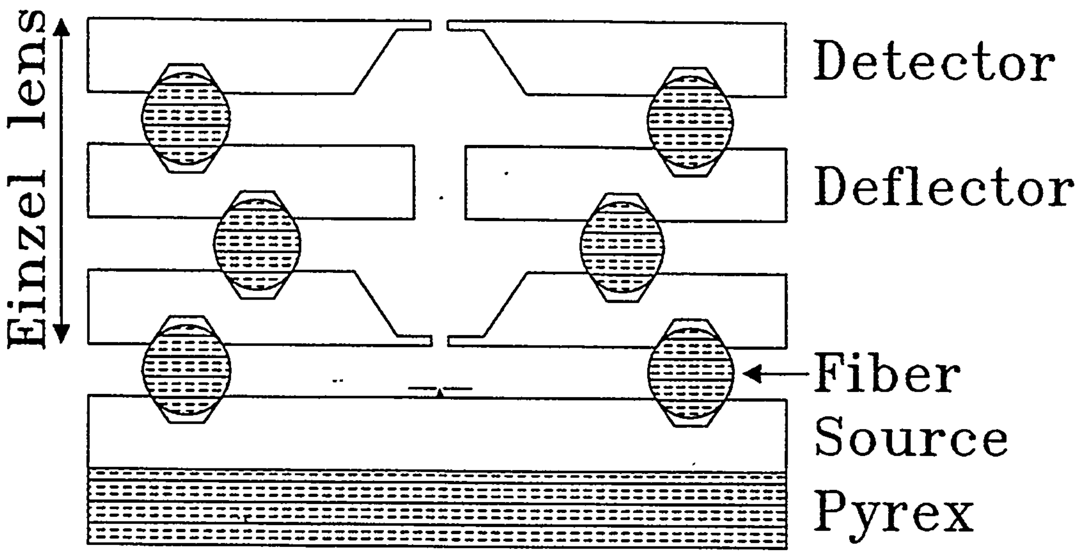

Fig. 3.

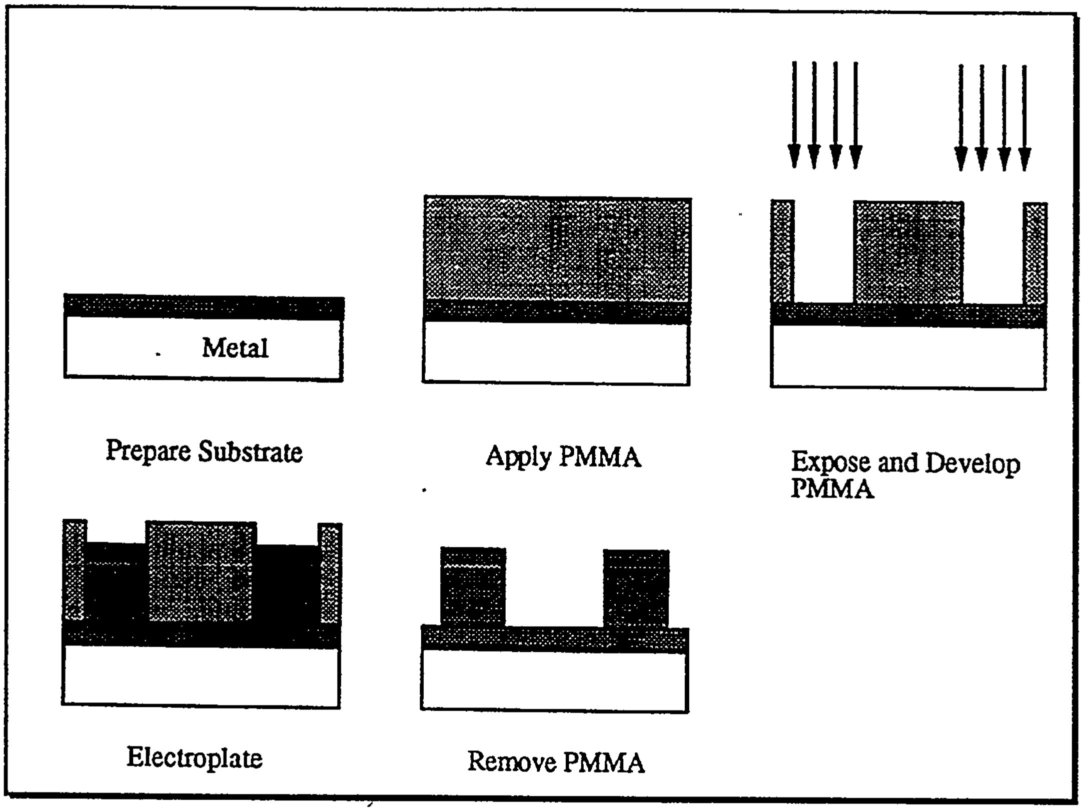
Metal
Prepare Substrate
Apply PMMA
Expose and Develop PMMA
Electroplate
Remove PMMA

Fig. 4.

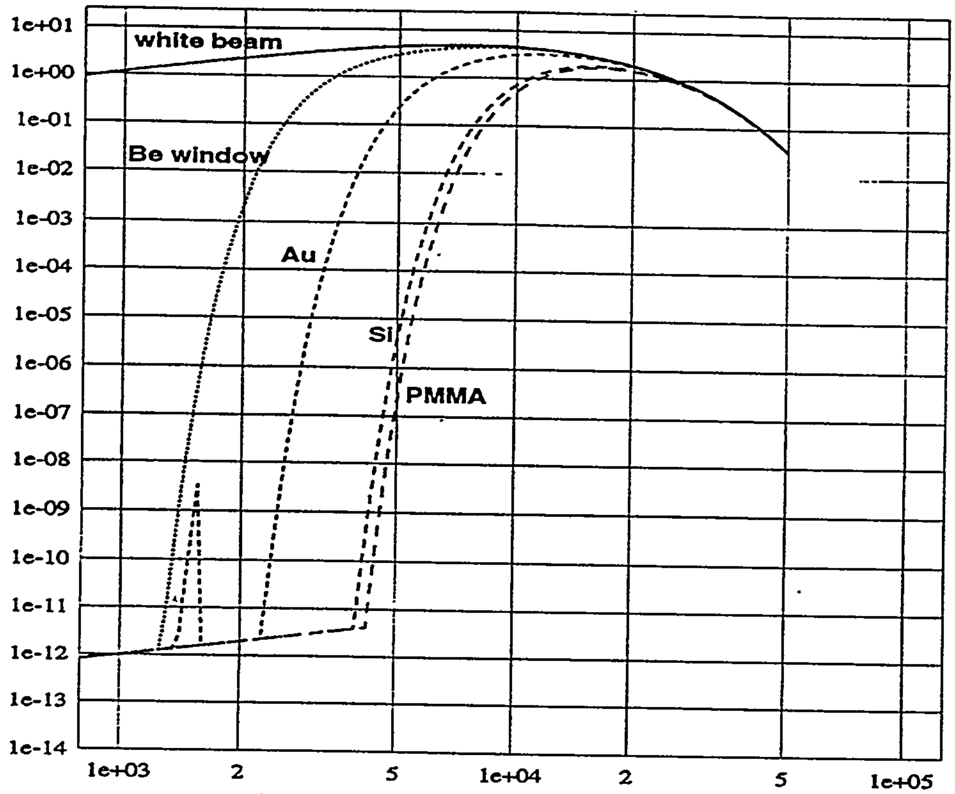
1e+01
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
1e-14
1e+03
2
5
1e+04
2
5
1e+05
white beam
Be window
Au
Si
PMMA

Fig. 5.