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LIGA FABRICATION OF MM-WAVE ACCELERATING CAVITY STRUCTURES AT THE ADVANCED PHOTON SOURCE (APS)

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Abstract

Recent microfabrication technologies based on the LIGA (German acronym for Lithographe, Galvanoformung, und Abformung) process have been applied to build high-aspect-ratio, metallic or dielectric planar structures suitable for high-frequency rf cavity structures. The cavity structures would be used as parts of linear accelerators, microwave undulators, and mm-wave amplifiers. The microfabrication process includes manufacture of precision x-ray masks, exposure of positive resist by x-rays through the mask, resist development, and electroforming of the final microstructure. Prototypes of a 32-cell, 108-GHz constant-impedance cavity and a 66-cell, 94-GHz constant-gradient cavity were fabricated with the synchrotron radiation sources at APS and NSLS. This paper will present an overview of the new technology and details of the mm-wave cavity fabrication.

1 INTRODUCTION

All new concepts for proposed accelerators such as next-generation linear colliders or muon colliders require substantial advances in the area of the rf technology. For example, to maintain a reasonable over-all length at high center-of-mass energy, the main linac of an electron-positron linear collider must operate at a high accelerating field gradient. Scaling accelerating structures to significantly higher frequencies could provide higher field gradient as proposed by P.B. Wilson [1].

The new micromachining technology, known as LIGA, consists of deep-etched x-ray lithography (DXRL), electroplating, and micro-molding. The microfabrication processes have been developed by W. Ehrfeld and co-workers to the degree that sub-millimeter actuators, motors, and gears can be built with great accuracy and a high aspect ratio [2]. Electric field levels as high as 50 MV/m and magnetic field levels of 1 T have been achieved with components. This technology could offer significant advantages over conventional manufacturing methods in such areas as precision fabrication and mass production.

The idea of applying these techniques to develop rf cavities for mm-wave linacs [3], undulators [4], free-electron lasers [5], and mm-wave amplifiers originated at Argonne National Laboratory in 1993. A meter-long structure with similar accuracy that also provides channels for vacuum pumping, adequate cooling, and focusing elements for beam dynamics can be built. 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 toward meeting these challenges.

2 MM-WAVE STRUCTURES

Due to DXRL's ability to maintain precise tolerances, it is ideally suited for the manufacture of rf components operating at frequencies between 30 GHz and 300 GHz. The first two structures fabricated were a 32-cell, 108-GHz constant-impedance cavity and a 66-cell, 94-GHz constant-gradient cavity. A 32-cell, 108-GHz constant-impedance cavity is a planar accelerating structure; its linac application has been investigated thoroughly, and its parameters are shown in Table 1. In changing from a typical cylindrical symmetrical disk-like structure to a planar accelerating structure, there is less than 5% loss in shunt impedance and Q-value. For a practical micro-linac application 10 MV/m is chosen in the accelerating gradient, but the accelerating gradient is not limited to that when the rf system is operational in the pulse mode with less repetition rate.

Table 1: The rf Parameters of a 32-Cell, 108-GHz Constant-Impedance Cavity

Frequency	f	108 GHz
Shunt impedance	R	312 MΩ/m
Quality factor	Q	2160
Operating mode	TW	2π/3
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

For a constant-impedance planar structure, the double-periodic structures with confluence in the π-mode designs were considered. The 2π/3-mode operation in these structures can give high shunt impedance, group velocity, and low sensitivity on dimensional errors. More detailed descriptions such as rf simulation using the MAFIA computer code and the thermal analysis related to this structure can be found in Refs. [6, 7].

The constant impedance structure is simple and can be easily fabricated, but may not be the best for accelerator applications, especially due to the difficulty of heat removal in the microstructure. In a constant-impedance structure, the concentration of heat at the structure input

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can limit the high power rf operation of the structure. To have higher shunt impedance of the structure, the thickness of the irises between the cells must be small (say $< 0.1\lambda$). However, heating imposes a limit in this case; heating at the center of the irises limits the maximum input power. Successful heat removal and uniform heat loading throughout the structure are important for optimum performance of the mm-wave accelerating structure.

The constant-gradient linear accelerating structure has been used in many present accelerators due to its higher energy gain and better frequency characteristic. The constant-gradient structure has higher shunt impedance and more uniform power dissipation, and is less sensitive to frequency deviations and beam break-up when compared to the constant-impedance structure. The control of cell-to-cell coupling in the side-coupled structures can be made to realize the constant-gradient planar structures.

The one limiting factor in the micromachining process is that the planar structure has to have uniform indentations on a planar wafer. Using microfabrication technology, it is more difficult to realize a constant-gradient structure than a constant-impedance structure. Changing the group velocity along the structure while keeping the gap and cell depth dimensions constant is difficult. Since the structure needs to be manufactured on a planar wafer, adjusting the cell width and length with a constant depth within the structure is necessary. A constant-gradient structure can be realized with a cut in the iris between the adjacent cavity cells along the beam axis in each half structure. Figure 1 shows the constant-gradient structure with cuts in the irises and its rf parameters are summarized in Table 2.

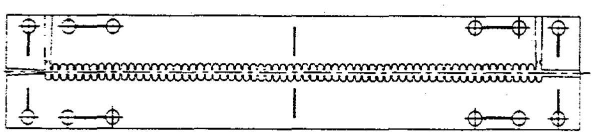

Figure 1: The 66-cell, 94-GHz constant-gradient cavity.

Table 2: 94-GHz Linac/rf Parameters

Parameter	Symbol	Value
Beam energy	E_o	50 MeV
Avg. beam current	I_b	1 mA
Frequency	f	94-GHz
Field gradient	E	10 MV/m
Mode of operation	TW	$2\pi/3$
No. of cavities	N	66
Structure length	l	7 cm
rf power	P	29.1 kW

3 FABRICATION

The simplified version of the DXRL process is shown in Fig. 2. It consists of making an 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.

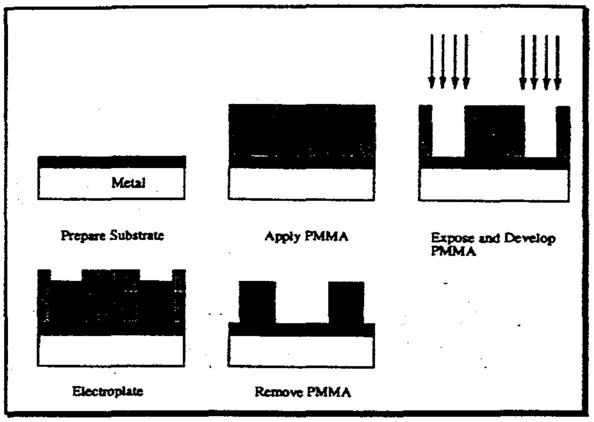

Figure 2: Simplified DXRL process.

DXRL with high-energy synchrotron radiation allows resists up to 1000 μm thick to be fabricated with submicron accuracy. A high-accuracy DXRL mask was made by means of an intermediate mask--that is, in two steps. The first step was the photolithography. 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. The second step used soft x-ray lithography at the Center for X-ray Lithography in Stoughton, Wisconsin (1-GeV Aladdin). For the DXRL mask, 45-μm Au was plated over a 300-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 [8]. To avoid alignment problems and x-ray fluorescence, these two steps were done on the same sample substrate without a physical gap.

Poly-methylmethacrylate (PMMA), up to 1-mm thick, was used as a positive resist. The copper substrate was diamond-finished to have a flatness of 1 μm over 4 inches. Then either an oxide film was grown to one micron thick or an equally thick Ti coating was deposited in order to promote better adhesion to the copper substrate. Through these processes, the flatness of the copper surface is maintained but still rough enough to give a good adhesion to the PMMA sheet (the roughness of less than 0.1 μm) [9].

When the PMMA film was cast onto the copper substrate, it was then annealed at various temperatures 110 - 170° C for one to three hours [10]. The NSLS (National Synchrotron Light Source) beamline X-26C and the APS 2-BM-A beamline were used to expose the sample. The transmitted x-ray intensity was calculated based on the APS bending magnet parameters and is plotted in Figure 3. The ratio of the top dose to the bottom dose for the 1-mm-thick PMMA is about 1:1. During the exposure, the sample was enclosed in a He-purged housing with a Kapton window, and the sample holder baseplate was water-cooled. The first platinum mirror with a grazing angle of 0.15° was used to cut off all the high energy x-rays above 40 keV as shown in Figure 3. More information on the APS 2-BM beamline for the DXRL can be found in Ref. 11.

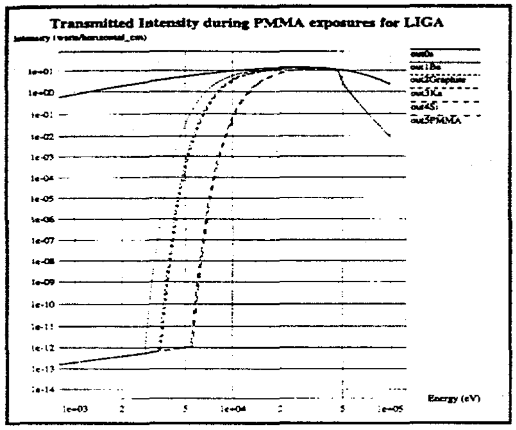

Figure 3: Transmitted x-ray intensity during PMMA exposures for DXRL at APS, energy (eV) vs. intensity (W/cm^3).

Two different developers were used in the developing process. The first developer was a mixture of 60% vol 2-(2-butoxy-ethoxy) ethanol, 20% tetrahydro-1, 4-oxazine, 5% 2-aminoethanol-1, and 15% DI water [12]. The allowed dose range was 3 to about 10 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. The final electroplated structure for the prototype of the 108-GHz constant-impedance cavity structure is shown in Figure 4.

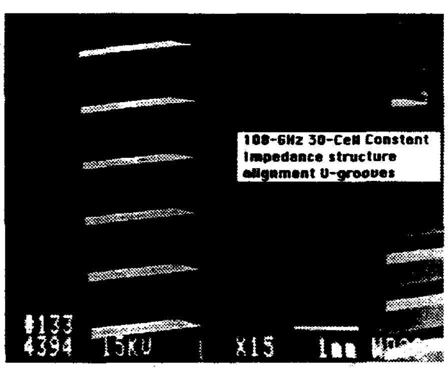

Figure 4: SEM picture of the 108-GHz constant-impedance cavity structure.

4 SUMMARY AND FURTHER WORK

- To get a size-controllable structure, details of both the developing process (for example, use of ultrasonic cleaning) and electro-plating process (pulse mode operation) has to be optimized.
- Two mirror-imaged fabricated structures for the 108-GHz constant-impedance cavity are being aligned ready for network measurement.
- The metallurgical study of the copper-electroplated sample, recently done by C. Pearson at SLAC, shows that the level of oxygen in the sample appears to be too high, one has to improve the electroplating process for vacuum/high power rf.
- The bead-pull measurement setup for the LIGA-fabricated mm-wave cavity structures is underway.

5 ACKNOWLEDGMENTS

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