MICROCAVITY STRUCTURES*

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Abstract

The feasibility of building mm-wave cavities using deep x-ray lithography techniques is being investigated. These cavities could be considered for linac accelerating structures, undulators, free electron lasers, or mm-wave amplifiers. The construction process includes making precision x-ray masks, x-ray exposure of poly-methyl-methacrylate (PMMA), removal of PMMA, and electroplating a metal. Highly precise two-dimensional features can be machined onto wafers by this technique. The challenge is to fabricate the wafers onto three-dimensional rf structures. Rectangular cavity geometry is best suited to this fabrication technique. Status of wafer manufacture, fabrication and alignment techniques using capillaries bonded in precision grooves, $2\pi/3$ 120-GHz linac structures, heat extraction analysis, and beam dynamics in a 5-meter-long 50-MeV linac will be discussed. Measurements made on 10X larger scale models that were built with conventional techniques will also be discussed.

Introduction

Deep aspect ratio machining using x-ray lithography, etching, and plating techniques have developed to a degree where submillimeter actuators, motors, gears, etc. can be built with great accuracy[1]. 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, undulators, free electron lasers, and mm-wave amplifiers started at Argonne National Laboratory in 1992 after discussions with and encouragement from Henry Guckel of the University of Wisconsin-Madison. Over the last few years, several collaborators have joined together from several institutions to investigate the feasibility of building mm-wave rf sources using the basic deep x-ray lithography (DXL) technique. A summary paper on the design parameters of a 50-MeV mm-wave linac was reported at the IEEE-IEDM Conference[2]. This paper represents a summary of the work from a team of collaborators, each member of which has made significant contributions towards the material presented in this paper. The interested reader is encouraged to go to the references for more complete details on the topics discussed in this paper.

The deep x-ray lithography techniques allow manufacture of very precise features, on the order of 25 to 125 Å, in wafers in a two-dimensional plane with perpendicular walls of a few millimeters depth and virtually no runout[1]. In order to make a three-dimensional structure, one must be able to mount and bond two wafers together with an accuracy of better than 5 microns, build meter long structures with similar accuracies that can provide channels for vacuum pumping, provide adequate cooling, and provide focusing elements for beam dynamics. The studies of the collaboration have been directed towards meeting these challenges.

Basic Concept

The basic elements of a mm-wave accelerating structure are shown in Fig. 1. Because the DXL structure is fabricated using wafer technology, the rf structure is a series of rectangular cavities. The features are machined on wafers by the technique described in the next section. The nominal dimensions of a single cavity are on the order of a mm or less with a 0.1% machining precision. Two wafers are aligned over one another using alignment and bonding techniques developed by Alan Feinerman at the University of Illinois-Chicago[3] for micromachined electron microscopes. 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. The features of a subcentimeter, scanning electron microscope fabricated by this technique are shown in Fig. 2. Meter long structures are envisioned by longitudinally staggering the top and bottom wafers to bridge across standard die sizes.

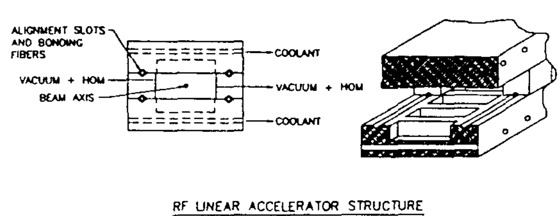

Fig. 1 Pictorial view of a 120-GHz rf structure fabricated by deep x-ray lithography techniques

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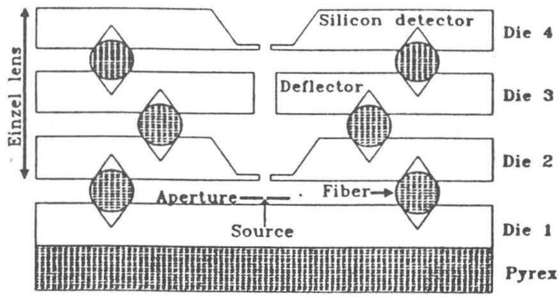

Fig. 2 Subcentimeter SEM

Coolant flows across the top and bottom of the structure as shown in Fig. 1. 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.

The electron beam is confined to the central region of the structure either the micromachined magnets or by rf phase focusing using the rectangular field modes proposed by H. Henke[4].

Fabrication of Structure

Traditional mechanical machining and finishing methods will not yield the 5-micron tolerances required for this waveguide. In fact, only lithographic/chemical etching systems approach the tolerances desired. The DXL technique was used to make the 240-GHz waveguide shown in Fig. 3. The dimensions of a single cell are 1.8 mm by 0.3 mm and each cell is separated by 0.1 mm.

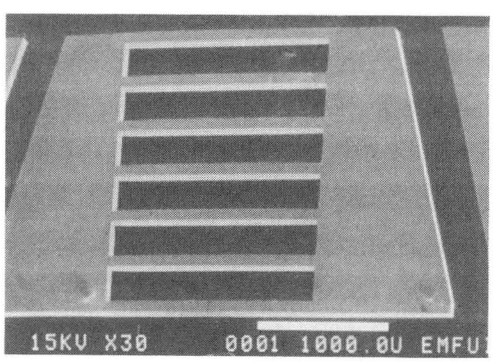

Fig. 3 SEM micrograph of (dimensions) rectangular cavities manufactured using DXL technique

A double-polished silicon wafer with SiO_2/Si_3N_4 films was used as a base substrate. A thin film of 100 Å Ti, 100 Å Cu, and 100 Å Ti was deposited as an electroplating base. PMMA was cast to a thickness of 200 μm and cured. An optical lithography mask was used to create a high-contrast x-ray projection mask, which was then used at the 1-GeV CXrl Aladdin accelerator to expose feature negatives into the PMMA. Nickel was plated into the PMMA pattern to form one half of the planar waveguide. The PMMA was removed to reveal the unfinished structure. Characterization of the plated surface indicated a 1-2 μm average roughness and a minimum to maximum height variance of 16 μm. Parallel lapping or diamond turning would be required in the final structure to improve these tolerances.

The microassembly of two structures created in the manner described previously was accomplished using a pair of x-ray patterned rectangular grooves. Pyrex capillaries (OD = 484 μm) were placed into the grooves and a polymer adhesive was used to fix the structure (Fig. 4). A 300-μm aperture was defined using this method, with an overall alignment accuracy of ± 5 μm, which is not unreasonable considering the calculated geometrical error due to the unfinished top Ni surface.

Proof-of-Principle Linac Concept

The frequency range for which DXL techniques appear most applicable is about 50 to 250 GHz. The heating due to wall currents at the multi-GHz frequency probably will limit operation to about 10 MV/m. If conventional type mm-bore quadrupole magnets are considered as focusing elements, the achievable gradients could probably be as high as hundreds of T/m, far higher than required.

A double-sided, muffin-tin structure was used as a model for a proof-of-principle, 120-GHz, 50-MeV linac. ANL originally developed a π mode structure, but switched to $2\pi/3$ traveling wave mode developed by H. Henke during a visit to ANL[5,6].

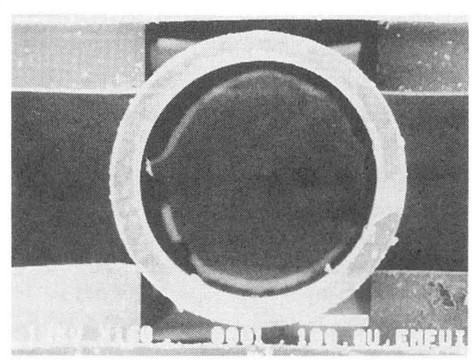

Fig. 4 Micrograph of a 484μm capillary in rectangular grooves

Further work has been done by Yoon Kang and others at ANL, and Heino Henke has been investigating side-coupled $\pi/2$ structures. The cross-section and the dimensions of the structure are shown in Fig. 5. The field, coupling, etc. were calculated using the MAFIA code[7]. The parameters for this proof-of-principle linac are given in Table 1 and the rf properties are given in Table 2.

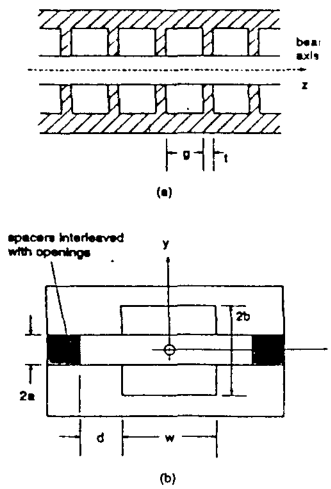

Fig. 5 Double-sided muffin-tin structure
(a) longitudinal cut (b) transverse cut
a = 0.3, b = 0.9, w = 1.8, d = 0.8,
g = 0.633, t = 0.2

Table 1
mm-Wave Linac Parameters

Energy	**E**	**50**	**MeV**
Beam current	**I**	**1**	**mA**
Normalized emittance	ε_n	**1**	**πmm-mrad**
Field gradient	E	**10**	**MV/ m**
Beam pulse length	τ_p	**1**	**μsec**
Operating frequency	**f**	**120**	**GHz**
Energy spread	ΔE	**±0.1%**	
Duty factor	**DF**	**1%**	

Table 2
Muffin-tin Cavity rf Parameters

Frequency	**f**	**120**	**GHz**
Shunt impedance	r_0	***312***	***MΩ/m***
Quality factor	**Q**	**2160**	
Operating mode	**TW**	**2π/3**	
Group velocity	v_g	***0.043 x c***	
Attenuation factor	α	**13.5** m^{-1}	
Accel. gradient	E	**10 MV/ m**	
Peak power	**P**	**29.1 kW**	

The double-sided, muffin-tin structure, unlike cylindrical accelerating structures, does not possess axial symmetry. This must be considered in the design and, in fact, can be used in an alternating phase focusing scheme, as suggested by H. Henke[4]. Calculations for the $2\pi/3$ muffin-tin structure were performed by Mills and Nassiri[8]. To study the beam transport in the mm-wave linac, the particle tracking computer code *elegant*[9] was used. The tracking was done by providing the electromagnetic field distributions with appropriate boundary conditions in the muffin-tin cavity and performing numerical integration of the equations of motion. The initial input beam parameters to *elegant* are the rms beam sizes and the energy spread of the rf gun. The schematic is shown in Fig. 6. In these simulations we assume an accelerating field gradient of 10 MeV/m. The space charge effects are neglected since the injected beam energy is assumed to be 2.5 MeV for an average beam current of 1 mA. The tracking results for 400 particles indicate that without solenoidal focusing at low energy (up to 5 MeV), the maximum beam envelope size exceeds the accelerating structure aperture and significant beam loss will occur. A solenoidal field of 1.5 Tesla around the first section of the accelerating structure is sufficient to confine the maximum beam size within the aperture (see Fig. 7). After the first section, electrons emerge with energy of approximately 10 MeV. A simple FODO array with electromagnet quadrupoles is used for focusing after 10 MeV. A 5-meter structure would be needed to achieve 50 MeV. The beam transport efficiency from the rf gun at 50 MeV is 92%.

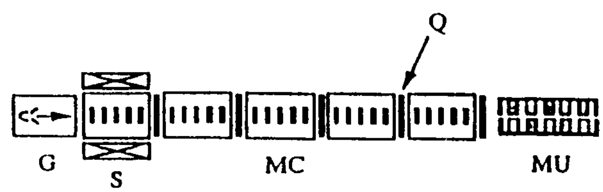

Fig. 6 A schematic of the mm-wave linac layout.
G: rf gun, MC: muffin-tin cavity, S: solenoid,
Q: quadrupole, MU: microwave undulator

Thermal Modelling

The finite difference electromagnetic code MAFIA[7] was used to calculate the rf power absorbed in the structure. Simulations indicated that if the structure is operated CW at room temperature with a 10 MV/m accelerating gradient, approximately 4400 W are absorbed per 7-cm section, resulting in a peak of 630 W absorbed in the first cell of each section. This leads to a peak heat flux of 8000 W/cm^2. Vacuum and structural stability concerns limit the maximum temperature rise to ≈ 60°C making CW operation extremely difficult. Therefore, for the preliminary studies, a duty cycle of 1% was used which lowered the time-averaged heat flux to a more reasonable 80 W/cm^2. Finite element simulations with this heat load showed that an advanced cooling scheme such as microchannels is needed. With a simulated microchannel cooling of 10 W/cm^2-K, the maximum temperature (which occurs at the top of the center of the iris) is 42°C.

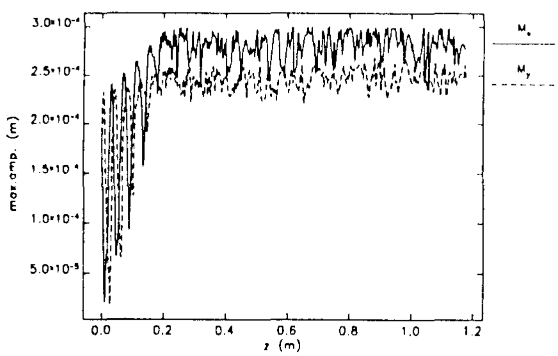

Fig. 7 Electron beam size in the first section of the mm-wave linac

The assumed effective film coefficient of 10 W/cm^2 - K is readily achievable using microchannels. Optimization of the channel geometry and coolant delivery can lead to effective film coefficients of ≈ 30 W/cm^2 - K. Such a film coefficient would lower the maximum temperature rise to 34°C.

Additional improvements in the maximum permissible heat flux and operating temperature may be achieved by taking advantage of the temperature dependent properties of copper. Operation at 77 K (liquid nitrogen) lowers the surface resistance which in turn lowers the absorbed power. Lowering the operating temperature may have an added advantage of increasing the thermal conductivity of the substrate. Considering all factors, maximum heat fluxes of ≈ 1000 W/cm^2 - K which would allow duty cycles up to 13% could be tolerated when operating at 77 K.

A thermal element transient analysis was also carried out for the structure. An average uniform heat load of 80 W/cm^2 was assumed. The maximum temperature was reached after ≈ 0.2 second. Next, the actual 60-Hz pulsed load was simulated. The results indicate that a maximum transient temperature of 80°C is reached upon application of each pulse. This short transient poses severe problems regarding structural stability and alignment. This problem may be reduced by increasing the repetition rate. The transient response for various repetition rates was modeled. A 480-Hz rate reduces the maximum transient to a more tolerable 50°C.

Vacuum

For proper operation of the accelerating structure, it has been estimated that a vacuum of 10^{-7} Torr is required on the beam axis. The side openings of the planar geometry provide convenient vacuum pumping slots. The proposed use of optical fiber spacers lying along the length of the structure inhibits this pumping scheme. Studies were carried out to investigate the pumping slot size needed to maintain the required vacuum. For calculations, it was assumed that the structure resided in a vacuum chamber with a vessel pressure of 5 x 10^{-11} Torr and that the copper outgassing rate was 1.1 x 10^{-12} Torr*liter/cm^2-s. It should be noted that the copper outgassing rate may not be valid for electroplated copper. Simulations showed that a 600-μm-long pumping gap must be provided in the alignment fiber approximately every 3 mm. The results were very dependent on the pyrex fiber outgassing rate. The fiber outgassing rate must be on the order of 10^{-9} Torr*liter/cm^2-s in order to maintain the desired vacuum level on the beam axis.

RF Tests on 10X-Scale Models

Twelve-GHz models of the 120-GHz structures mentioned above have been built at Argonne and at the Technical University of Berlin. In order to make the tests, an input coupler was designed[10] and built into the model. The parameters for the 12-GHz, $2\pi/3$ muffin-tin, 10X scale model are given in Table 3. The phase advance per cell was measured using the nodal shift technique by moving a rectangular plunger along the structure[11]. The results are shown in Fig. 8. The phase advance per cell is close to 120° but not quite uniform. The nonuniformity is probably due to limited machining accuracy on this model. Also, tuning of the input/output coupling cavities needs to be improved.

Table 3
Electrical Parameters of the 12-GHz, 10X Scale Model of the $2\pi/3$ Muffin-Tin Structure

Frequency (GHz)	12
Q	6821
r_0 (MΩ)	98.6
k	0.0474
v_g/c	0.043
$\alpha(m^{-1})$	0.428
ℓ (cm)	68.3
τ	0.292
T_{fill} (nsec)	52.9

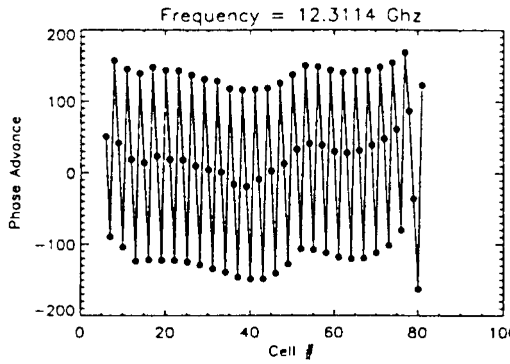

Fig. 8 Measured phase advance between the accelerating cells for a $2\pi/3$ mode

Summary

Over the last few years, considerable study has gone into the feasibility of building mm-wave rf structures. The goal to prove feasibility has not yet been achieved, but results of the studies are encouraging. Rectangular modes suitable for acceleration can be generated in DXL-built structures: techniques for alignment, fabrication, and mechanical bonding of the wafers appear feasible; alignment of long structures, several meters in length, probably can be built to an accuracy of ± 1 or 2 μm; cooling of the structures in pulsed mode is possible; although not discussed in this paper, superconducting niobium might make CW operation feasible; and the beam transport throughout a 5-meter-long accelerating structure with estimated construction tolerances would appear to be possible with minimum beam loss.

The possibility of building mm-wave undulators and FELs that would match to a mm-wave linac are being studied. It is premature to report on these studies, but the goal would be to build small, tunable, coherent synchrotron radiation sources in the VUV and hard x-ray regime.

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