U.S. DEPARTMENT OF ENERGY NUCLEAR ENGINEERING EDUCATION RESEARCH: HIGHLIGHTS OF RECENT AND CURRENT RESEARCH—III

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1. Novel X-Ray Source at the RPI Linac, *Y. Danon, B. A. Sones, R. C. Block (RPI)*

A novel, tunable X-ray source using the 100-MeV electron linear accelerator at Rensselaer Polytechnic Institute is currently under development. The X-rays are generated from the interaction of relativistic electrons with the periodic structure of single crystals. A broad distribution of "virtual photons" is associated with electrons moving through a medium at relativistic speeds. These photons diffract according to Bragg's Law. This results in the production of Parametric X-rays (PXR) emitted with various energies at different positions with respect to the crystal. These PXR have several novel and useful characteristics. The radiation is emitted with a unique angular distribution of two Lorentzian cones, separated by an angle of about 10 milliradians from the Bragg angle, with zero intensity precisely at the Bragg angle. The energy of the PXR is solely determined by the orientation of the incident electron and the diffracting crystallographic planes. Rotation of the crystal with respects to the electron beam allows the PXR energy to be tuned. The natural energy spread of the PXR is on the order of several eV [1] and the observable width depends on the geometry of the experiment. PXR can be emitted at large angles relative to the electron beam, which helps avoid the bremsstrahlung background.

Baryshevsky et al. [2] produced the first experimental realization of PXR in Tomsk (former Soviet Union) in 1985 using 900-MeV electrons and a diamond crystal. Because of high electron energies and current, synchrotrons like those in Tomsk as well as Germany (MAMI) [1] and Japan [3] have been first used for producing and characterizing PXR. Since 1990, linear accelerators have also been used for researching PXR with the promise of less expense, less residual radiation, and greater portability. Shchagin [4] at Kharkov LINAC (Ukraine) characterized the polarity and right angle emission of PXR; Fiorito et al. [5] used facilities at the Naval Post Graduate School, California to produce the first PXR outside of the former Soviet Union; Freudenberger et al. [6] assessed PXR intensity at the S-SALINAC (Germany); and Akimoto et al. [7] examined crystal thickness and rotation effects at the Hokkaido accelerator in Japan. Much has been proposed for the PXR applications; most recently Fiorito et al. [8] theoretically investigated the use of PXR towards mammography imaging. However, a frontier exists in bridging the gap between PXR production and useful PXR applications.

The objective of this investigation is the optimized production of PXR for future applications in medical imaging, material characterization, and detection of explosives and nuclear materials. The investigation has three phases: theoretical optimization and experiment design, data acquisition, and data analysis. The experiment is designed to maximize photon flux and minimize the energy spread for the desired photon energy, which may range from 10–100 keV depending on the application. While considerations for the electron beam, crystal positioning device, and the detection system are important steps, the forefront of this optimization rests with the crystal characteristics. The following were considered: crystal structure; lattice parameters (size); bulk thickness; electric, thermal, and absorptive properties; and the growth and polishing techniques.

Figure 1 presents theoretical calculations for a variety of well-documented single crystals to include Si, Ge, Cu, Pyrolytic Graphite, and W. PXR intensities were calculated for (111), (220) and (002) planes at Bragg angles from 5 up to 90 degrees. The differential intensity at the peak of one of the angular distribution cones was integrated across a 1 mm^2 detector surface placed at a distance of 1 m from the crystal. For each crystal the peak intensity appears at a different Bragg angle and different X-ray energies.

Pyrolytic graphite shows the most promise for photon energies less than 25 keV while copper and tungsten are best at higher energies. However, the mosaic spread of the graphite might degrade these results, and this will be further investigated.

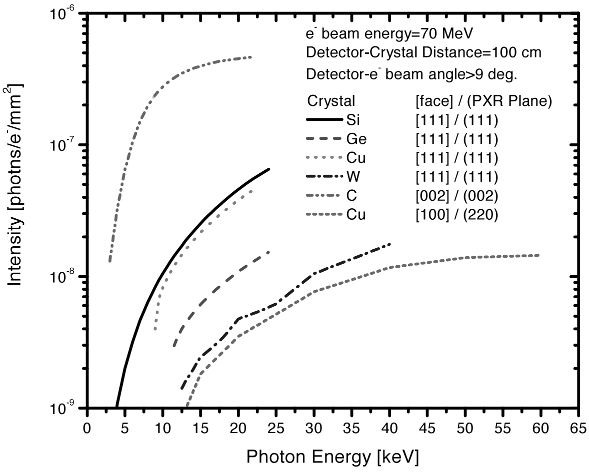

Fig. 1. Calculated X-ray intensities for several 500 μm thick crystal targets for several reflection planes and crystal face planes. The upper energy limit of each case was limited by a requirement of an angle of more than 9 deg between the detector and the electron beam axis.

PXR have an inherently narrow line shape, and the dominant broadening effect comes from the experimental set-up. Contributing factors are electron beam spot size and beam divergence, crystal thickness, and X-ray collimation. These effects vary with experimental parameters, but the most problematic factor in the small angle experiment is the beam divergence. Other considerations for broadening come from electron scattering from the accelerator window and from the crystal, heat deposition in the crystal, and associated bremsstrahlung generated along the path of the electron. Monte Carlo transport is used to assess these effects.

So far our work has concentrated on theoretical calculations of PXR production and the specifications of optimal experimental conditions necessary to maximize PXR intensity and minimize its energy spread. We are now finishing the optimization calculations and entering the experimental phase.

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2. Radioisotope Power for MEMS Devices,

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INTRODUCTION

Micro Electromechanical Systems (MEMS) are fabricated devices with dimensions in the micrometer range. For many applications an on-board power source is required, but none is currently available commercially. There is ongoing work studying the use of chemical batteries and fuel cells, among other technologies, for powering MEMS devices, but nuclear sources offer an advantage over these others when either long life or very high power density is required. In this paper we explore two novel approaches for incorporating a nuclear source into a silicon-based, diode-type device for producing power from radioisotopes. In addition, an application is presented, with the goal of using radioisotopes to power an RF antenna for wireless communication. In concepts such as "smart dust" [1], where small sensors communicate with each other to relay information to a central server, wireless communication will be vital, and a nuclear approach will allow this in situations where refueling is not feasible and long life is required.

APPROACHES

Due to the small size of MEMS devices, incorporation of the source into the device can be challenging. With 63-Ni, we have had success [2, 3] with incorporation of a liquid source into devices, and have electroplated the source onto other devices. With tritium, though, these options are less desirable. Hence, we have pursued incorporation of tritium into the devices by obtaining glass beads containing lithium, irradiating the beads with neutrons to form tritium, and then incorporating the beads into the MEMS devices.

Glass beads with diameters of 20 to 50 microns containing 6-Li were placed in an aluminum tube that was then placed in a larger aluminum cylinder. The cylinder was filled with water to help cool the aluminum tube during irradiation (a finite element thermal model predicted bead temperatures below 360°C). We placed 0.246 grams of beads into the tube and irradiated them for 37 minutes in a 1 MW TRIGA reactor. This process produced approximately 2 mCi of tritium in the beads. The beads were then placed in a device for power production.

An alternative method for incorporating radioisotopes into the device is evaporation of a liquid source. One concern is the possibility of the radioisotopes leaving the surface as the liquid evaporates. To test this, we prepared 6 silicon samples and placed varying amounts of source on each. The liquid was then allowed to evaporate (at 93°C to hasten the evaporation) and the activity of the sample was measured. The measured activity of these samples increased linearly with the source volume and was consistent with the activity placed on each sample. Hence, evaporation does not seem to allow any of the 63-Ni to leave the surface.

An important application of nuclear power for MEMS devices is wireless communication. We have demonstrated the capability of producing RF transmission using radioisotopes for power. The concept requires a self-reciprocating metal beam [4], driven by a series of charges and discharges of the beam by collection of charged particles from a nuclear source.

Using a self-reciprocating beam, RF transmission can be produced by applying a thin film of piezoelectric to one side of the beam. The sudden discharge of the beam results in excitation of the beam, causing oscillations in the voltage as the strain in the piezoelectric varies. A typical trace of the voltage is shown in Fig. 1. This result is for a 100-micron thick beam electroplated with a 20-micron gold film to ensure absorption of all beta particles. The experiment is carried out in vacuum (40 mTorr), to avoid absorption of the betas before reaching the gold film and to prevent breakdown in the gap. The frequency of this oscillation is 258 MHz, ideal for RF transmission. Typically 0.04 pJ is radiated from the device over a period of approximately 2.5 microseconds resulting in a power of 20 nanowatts transmitted into space. Although this power is low, recent results in impulse-radar work [5] indicate that detectors to detect this power are available.

CONCLUSIONS

Radioisotopes have been incorporated into MEMS devices by several means. As an application of these techniques, we have