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Absorbed Dose Characteristics for the BST Thin Film Irradiation by the 5 MeV Electron Beam

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Abstract. The paper concerns the study of the ~5 MeV electron beam interaction with the thin layer experimental sample at the AREAL electron linear accelerator. The necessary exposure time and the irradiation effects parameters calculations have been performed using measured parameters of the beam and numerical simulations applying particle transport code FLUKA [1]. Numerical simulations with FLUKA provide estimation of the absorbed dose - the main parameter that defines the amount of the radiation induced crystalline structure defects. Calculations have been conducted for the experimental study of the irradiation effects on the parameters of the ferromagnetic composition $Ba_{75}Sr_{25}TiO_3$ - Barium-Strontium-Titanate (BST) thin film. The main goal reached is the calculation of the required exposure time taking into account beam intensity, energy, spatial and angular distributions and experimental sample geometrical shape, size, composition and disposition for obtaining intended value of the absorbed dose. Beam parameters used for numerical simulations have been obtained from beam diagnostic measurements.

Keywords: electron accelerator, irradiation, particle tracking simulation

1. Introduction

Ferroelectric thin films, particularly BS-based ones, have wide applications in multifunctional microelectronic devices [3-4]. The electric, dielectric, and Ferro-electric characteristics of these thin films can be modified via electron irradiation leading to microelectronic devices new performance [5–9]. The BST thin films have a low frequency dependence of the relative permittivity and dielectric losses. Those dependences can be substantially changed by the samples electron irradiation producing thin films with the properties adapted to the requirements of the application. The 4 MeV electron beam irradiation effects on the electric, dielectric, and ferroelectric properties of the BST film-based sensor (Fig. 1) have been studied in the frequency range from 100 Hz to 1 MHz's.

An experimental study has been carried out at the AREAL linear accelerator aiming at investigation of the effect of the irradiation by the 4.2 MeV electron beam on the electrical properties of the ferroelectric composition $Ba_{75}Sr_{25}TiO_3$ (BST). The paper is focused on the methods of the calculation of experimental sample irradiation parameters based on beam parameters measurement and numerical simulation study of the electron beam interaction with the BST material thin layer.

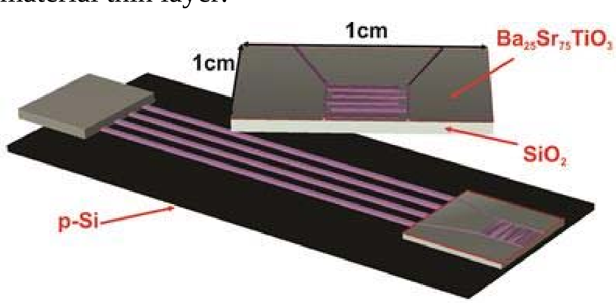

Fig. 1: Structure and parameters of experimental sample

Material	Thickness
$Ba_{75}Sr_{25}TiO_3$	300 µm
SiO_2	500 µm
p-Si	0.6 mm

Table 1: Structure of experimental sample

The experimental sample consists of three thin layers of rectangular cross section with different sizes and chemical composition (BST, SiO_2 and p-conductivity Silicon). Fig. 1 shows the parameters and the layer structure of materials.

AREAL electron linac can produce clean and controllable 2-5 MeV electron beam with 10-250 pC bunch charge and 1- 50 Hz repetition rate [2]. The main parameters of the electron beam can be monitored and manipulated to apply precise irradiation dose for the experimental sample. Main parameters of the AREAL electron beam are presented in Table 2.

Energy	2–5 MeV
Bunch charge	10–250 pC
Bunch length	0.4–9 ps
Norm. emittance	≤ 0.5 mm-mrad
RMS energy spread	≤1.5 %
Repetition rate	1–50 Hz

Table 2: AREAL beam parameters

2. Beam diagnostic measurements

Advanced Research Electron Accelerator Laboratory (AREAL) based on photo cathode RF gun is being constructed at CANDLE.

The AREAL RF photogun experimental operation provides the electron bunches with 4.2 MeV energy and 250 pC beam charge. The gun section contains the focusing solenoid, magnetic spectrometer, horizontal/vertical corrector magnet, Faraday Cups (FC) and YAG screens with cameras. The charge of individual bunches was measured using two FCs.

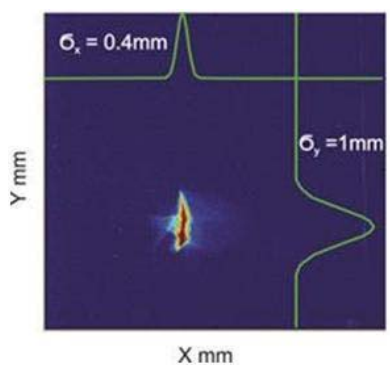

Fig. 2: Electron beam profiles downstream to photo-injector measured by YAG screen system.

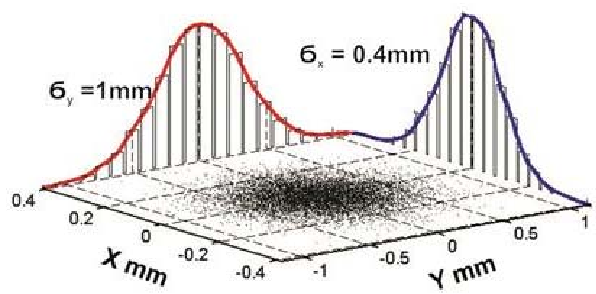

Fig. 3: The profile of the electron beam along the horizontal and vertical axes perpendicular to beam direction at the beam pipe window.

The beam energy and the energy spread measurements have been performed using the magnetic spectrometer located after the gun focusing solenoid. The spectrometer consists of 90° bending dipole magnet and the YAG screen. The beam absolute energy is determined by measuring the bunch position with respect to the central trajectory, which was calibrated with particle tracking simulations using the measured dipole magnetic field distribution. The energy spread is evaluated using the bunch horizontal profile at the YAG screen.

Fig. 2 presents the 250 pC charge beam profile at the YAG screens located downstream to the injector. The corresponding beam energy is about 4.2 MeV and the energy spread is below 2%. Beam transverse profile measurements results have been used (Fig. 3) to calculate absorbed dose spatial distribution. The particles energy spread is dominated by an uncorrelated contribution, which is decreasing during acceleration being inversely proportional to beam energy.

The barium strontium titanate ceramics has been irradiated by 4.2 MeV an electron beam at the AREAL. The samples were exposed to the electron beam at a distance 3cm from the exit port.

3. Numerical simulation with FLUKA

Absorption dose in the sample through the electron has been calculated using the particle transport simulation code FLUKA. The results of beam diagnostic measurements used for simulations include:

a) Beam current measurements by Faraday cup;

b) Beam transverse profile monitoring by YAG screen and camera station;

c) Focusing solenoid magnet current adjustment and definition of the beam minimal spot size;

d) Beam energy/momentum measurement by spectrometer consisting of dipole magnet and YAG screen system.

Figure 2 shows that the beam has Gaussian distribution of electrons along horizontal and vertical directions, i.e. perpendicular to the beam direction. Default function of FLUKA does not let to simulate the beam with required parameters. Default function is designed to calculate physical quantity per electron that gives only integral values of absorbed dose. Therefore a custom user routine was programed in FORTRAN language. The program is able to generate beam with the parameters and distributions that actually available at AREAL linear accelerator. Figure 5 shows the profile of the electron beam, being used for the FLUKA simulations.

It was obtained from the FLUKA numerical simulations that number of electrons incident on the experimental sample is 58.65 percent of the electrons beam that have reached the beam pipe exit port. Missing electrons have been absorbed by the 50 microns tick titanium exit window and while they traveling the distance of 3 cm in the air. Only 12.66 percent of the electrons that reached the BST layer have been scattered within the layer volume. The most of the electrons passed through the material without any interaction. In Fig. 4 it is shown the electron energy distribution change in result of the interactions of the electron beam with the BST layer. Distribution curve shift towards lower energies corresponds to the energy loss within the BST layer.

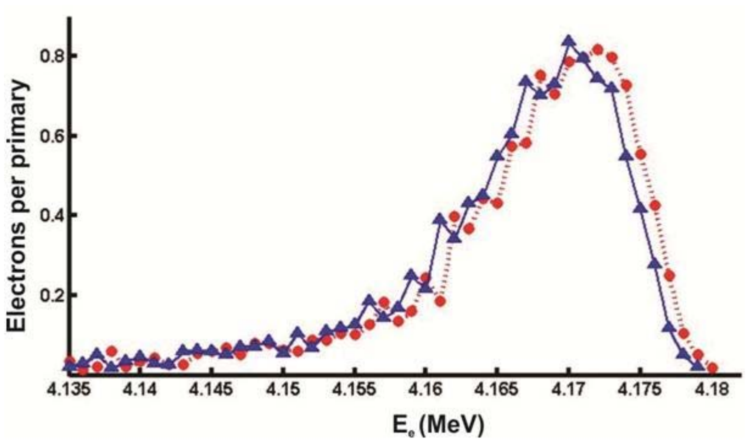

Fig. 4: Electron beam energy spectrum before (circles) and after (triangles) interaction with the BST layer obtained by numerical simulation. Distributions are normalized per primary.

It can be seen that energy losses of those electrons that interact with the matter are insignificant compared to their initial energy. Fig. 5 presents the absorbed dose (per electron) distribution along beam direction within the BST layer. The total absorbed dose in $Ba_{75}Sr_{25}TiO_3$ is 3.48×10^{-8}Gy per electron per second.

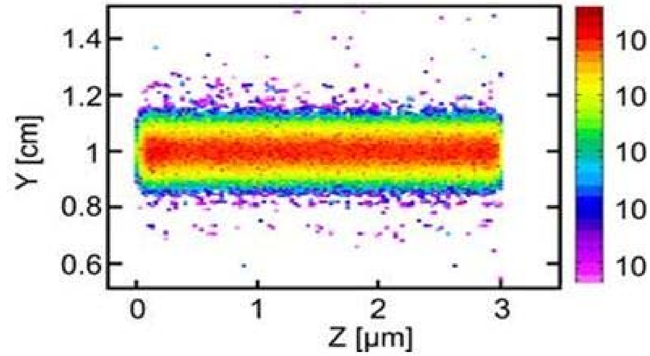

Fig. 5: Absorbed dose (unit: Gray = 1 J/kg) calculated distribution within BST layer. The Z points to beam direction.

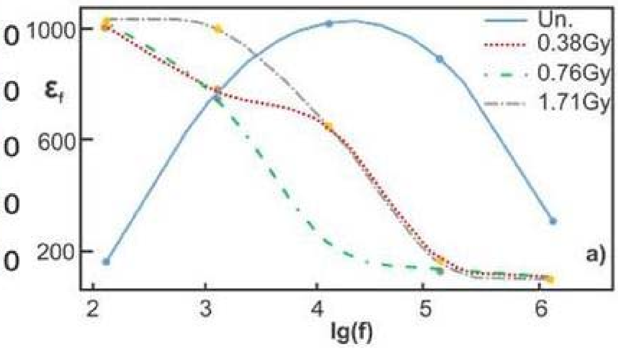

Fig. 6: Measured dependence of dielectric permittivity on frequency for unirradiated and electron-irradiated $Ba_{75}Sr_{25}TiO_3$ thin films.

4. Dielectric properties of BST thin films

The variation of room temperature dielectric permittivity's with frequency for unirradiated and electron irradiated (for delivered dose of 0.38, 0.76 and 1.71 Gy) $Ba_{75}Sr_{25}TiO_3$ thin films are as shown in Fig. 6. There is an appreciable change in the dielectric permittivity behavior after irradiation with different delivered doses. The room temperature dielectric permittivity of unirradiated BST thin films at 2kHz is 100. It has been observed to increase with the increase of delivered dose. The dielectric loss showed significant frequency dispersion for both unirradiated and electron irradiated films. Experimental measurements have been conducted using high resistance meter with the threshold of $10^{-6}\Omega$ and LCR meter with the frequency range up to1 MHz.

Summary

FLUKA simulations has been conducted aimed at calculation of the required exposure time to provide necessary irradiation dose for the given beam parameters (energy, current, spatial sizes and divergence).

Input parameters for FLUKA simulations of the electron beam interaction with experimental sample have been defined relying on two sets of the data. Beam diagnostic measurements results have been combined with the sample geometrical and composition parameters.

Calculated absorbed dose spatial distribution within the volume of the BST thin film has turned to be essentially uniform.

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