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Development of an X-ray tube for irradiation experiments using a field emission electron gun

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ABSTRACT

A new X-ray tube using a ring-shaped emitter as a field emission electron source has been developed. By using a ring shaped cathode, X-rays can be extracted along the axial direction through the central hole. This cylindrically symmetrical design allows for the tube to be arranged in the axial direction with the high voltage target at one end and the X-ray beam at the other. The newly developed X-ray tube can operate at a tube voltage of more than 100 kV and at a tube current of more than 4 mA, and can be used for irradiation experiments with an irradiation dose range from mGy up to kGy. The X-ray tube can be used immediately after turning on (i.e. there is no stand-by time). In the experimental model, we demonstrated stable electron emission at a tube voltage of 100 kV and at a tube current of 4 mA during a 560 h continuous test.

1. Introduction

X-ray irradiation experiments are used in many research fields. Low-dose radiation effect in animals at doses from 1 mGy to 10 Gy have been studied by many research groups (see Ref. [1], and references therein), and such studies are used to investigate the relationship between received dose and cancer risk. X-ray irradiated doses of kGy order were used in the irradiation of food to control pathogenic bacteria [2], and the evaluation of radiation damage in semiconductor devices [3]. In conventional X-ray devices, typically the cathode and anode are aligned along the axis of a cylindrical X-ray tube. X-rays are extracted in a direction perpendicular to the axial electron beam. The anode is heated by collision with electrons and must be cooled, and either the anode or cathode must be floated to high-voltage. If the X-ray beam is to be extracted in the vertical direction, the device should be arranged in the horizontal direction. In such an arrangement the space footprint of the device is large. Compact high voltage X-ray irradiation equipment is desirable because space is limited in the laboratory. Most X-ray tubes with a tube current of over 1 mA use a hot cathode type electron gun. Such hot cathodes have the disadvantage that some time is needed before they are operational, a stand-by time. Cold cathodes, on the other hand, need no warm up (stand-by) time and they can be formed in any shape required. X-ray tubes using a cold cathode can be used immediately. Various X-ray sources using carbon nanotubes (CNTs), carbon nanofibers or graphene flower cloth has been developed by many research groups [4–9]. Examples include compact X-ray sources [4,5], a micro-focused X-ray source [6], a micro-CT scanner [7] for X-ray inspection, a multi-pixel X-ray array source [8] for micro-radiotherapy, and a stable X-ray source [9] for irradiation system. However, those previous X-ray sources typically operate at accelerating voltages of less than 50 kV and lifetimes less than 100 h. One notable exception to this generalization are the cold cathode, high-energy (tube voltage of more than 150 kV), pulsed X-ray sources for X-ray inspection that have been developed by Golden Engineering, Inc. [10].

At AIST we have been developing compact, light-weight, long-lifetime X-ray tubes for X-ray imaging and X-ray fluorescence spectrometry using cold cathode electron emitters made from a particular type of chemical vapor deposition (CVD) grown carbon called Coniferous type Carbon Nano-Structure (CCNS) [11–13]. CCNS shows high stability at electron-current-densities of up to 100 mA/cm^2, which compares very favorably with CNTs [13], but it has proved difficult to make an emitter larger than around 16 mm in diameter. On the other hand, Pureron Co., Ltd have previously developed a different CVD based carbon emitter called Carbon Nano-structured Film (CNF) [14] as a field emission electron source grown to more than 40 mm in diameter on variously shaped emitter substrates. CNF can generate an electron-current-density of

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20 mA/cm^2. In this paper, we report the development of an X-ray tube for irradiation experiments using a CNF emitter.

2. Instrumentation

A schematic diagram of the newly developed X-ray tube for irradiation experiments is shown in Fig. 1. In the X-ray tube, all electrodes are cylindrically symmetrical, and X-rays are generated and extracted along the electron beam axis. The high voltage X-ray target and heat sink are arranged directly opposite the X-ray window. In this design the X-ray window is not influenced by the beam heating and the applied high-voltage on the X-ray target. The electron source is placed between the X-ray target and the X-ray window, and has an annular shape, with a central hole for X-rays to pass through. Emitted electrons from the emitter collide with the X-ray target generating X-rays. X-rays generated at the X-ray target pass through the hole in the center of the emitter and are transmitted through the X-ray window. The X-ray window and the emitter are kept at ground voltage. The potential of the X-ray target is set at positive high-voltage and determines the tube voltage. A grid is placed in front of the emitter surface. By adjusting the voltage on this grid the emission current from the emitter can be controlled, independent of the potential of the X-ray target. A focus lens between the grid and the X-ray target ensures the electron beam is adequately focused so that the X-ray spot size remains small. The focus lens is set at the same voltage as the grid.

The present cylindrically symmetrical design, in combination with extraction of the X-ray beam along the electron beam axis, allows several tubes to be arranged in close proximity in an array structure (see Fig. 2), greatly increasing the available irradiation area while maintaining a high dose rate. Large area multi-pixel X-ray sources have been designed [15] and built [8] by several groups previously. These sources are designed with the aim of X-ray imaging or producing a large area X-ray beam with a well-defined spatial distribution.

The electrodes in the experimental X-ray tube were designed with the aid of computer based simulations. The electric field and electron beam tracking were calculated by the finite-element analysis software Tricomp, version 8.0 (Field Precision, USA). A typical electron beam tracking result is shown in Fig. 3 where the distance between the emitter surface and the grid is fixed at 3 mm. In the newly developed X-ray tube, the voltage of X-ray

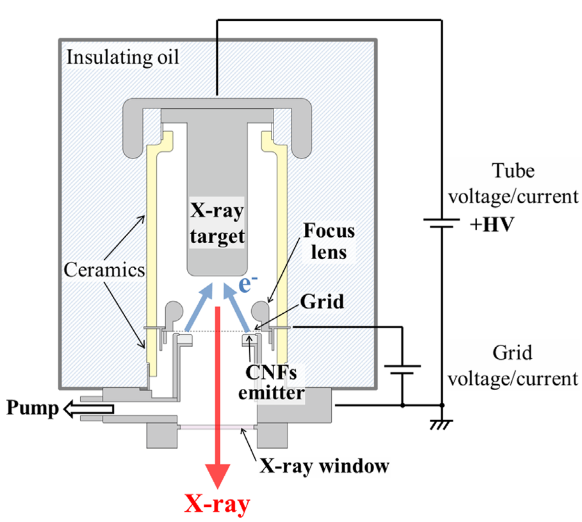

Fig. 1. Schematic diagram of newly developed X-ray tube for irradiation experiments.

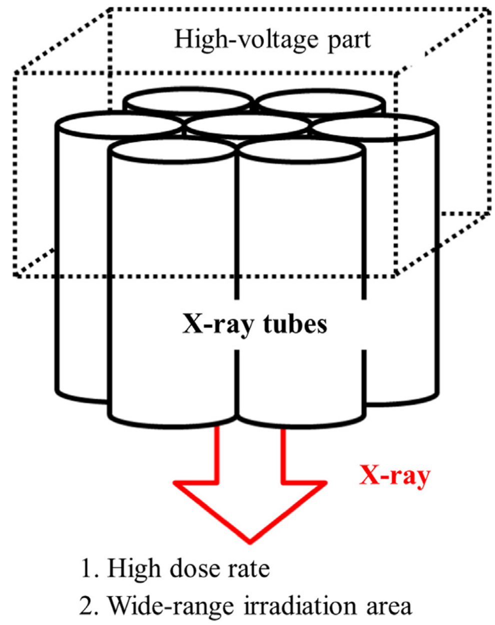

Fig. 2. The irradiation equipment for wide-range irradiation area and high dose rate using several present cylindrically X-ray tubes to be arranged in close proximity in an array structure.

target must be higher than the grid voltage in order to focus the electron beam. In Fig. 3(a), the voltages of the emitter, the grid, the focus lens and the X-ray target are set at 0 kV, 11 kV, 11 kV and 100 kV, respectively. The emitted electrons from the 40-mm-diameter emitter pass through the grid electrode, are focused to a beam by the focus lens, and are incident on the X-ray target. In all simulations, same focus lens was used, and deigned for focusing electron beam with no electron collision at focus lens and corresponding to wide tube voltage range of about 50–160 kV. Fig. 3(a) shows the results of three simulations using the same applied voltages but varying the distance between the X-ray target and the grid. At distances of 51.5 mm, 36.5 mm and 26.5 mm, the focused electron beam diameters are about 7 mm, about 10 mm and about 14 mm (with an internal diameter of about 9 mm), respectively. At the same applied voltage, the electron beam spot size is reduced when the distance between the X-ray target and the grid is increased. In Fig. 3(b), the voltage of the grid and the focus lens is reduced from 11 kV to 5 kV causing a reduction in the electron beam spot size from 14-mm to 10-mm. In Fig. 3(c), the voltage of the X-ray target is increased from 44 kV to 160 kV causing a reduction in the electron beam spot size from 20-mm to 11-mm. Therefore, in the newly developed X-ray tube, the electron beam spot size is reduced at the larger separation between the X-ray target and the grid, low grid voltage and high X-ray target voltage.

Neglecting absorption in the air, the irradiation dose value is inversely proportional to the square of the distance between the X-ray target and irradiated sample. Therefore, for high dose, it is desirable that the distance between X-ray target and the grid (and therefore the window) is minimized. In the experimental model, the grid – target distance was fixed at 26.5 mm corresponding to the simulation shown in Fig. 3(a). The X-ray tube voltage can be operated at more than about 4 times the grid voltage producing an electron beam with a spot size of about 20-mm-diameter (see Fig. 3(c)), smaller than the 25-mm-diameter hole in the center of the emitter.

Fig. 4 shows a comparison of the electric field on the surface of the substrate for a flat surface and an uneven surface containing regularly spaced ridges. In this simulation the distance between