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Event: SPIE Medical Imaging, 2021, Online Only

Development of microfocus X-ray source based on CNT emitter for intraoperative specimen radiographic system

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ABSTRACT

A microfocus X-ray source based on carbon nanotube (CNT) emitter grown by chemical vapor deposition is presented in this paper. The microfocus X-ray source is developed for the intraoperative specimen radiographic system, which can be used inside the operation theatre and helps reducing the surgery time during breast conserving surgery by confirming the extent of margin on specimen. This high focusing X-ray source is realized by growing CNTs on pointed structures. The field emission characteristic shows that maximum anode current of 1mA, which corresponds to a maximum emission current density of 500 mA/cm^2 from the CNT-based point emitter. The optimized parameter for the assembly of electron gun was achieved by using commercially available CST simulation software. Consequently, this microfocus X-ray tube could produce X-ray image of multilayer printed circuit board showing fine lines of integrated circuit.

Keywords: Breast specimen imaging, microfocus X-ray source, CNT, point emitter

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1. INTRODUCTION

In a normal protocol during breast conserving therapy, a specimen radiograph is taken to confirm the targeted lesion on the excised breast specimen [1]. With the advancement in portable X-ray systems, an intraoperative specimen X-ray system is available in market, which can efficiently take specimen radiograph inside the operation theatre and reduce the surgery time. In past 10 years, after introduction of this system, it has evolved from taking the specimen radiograph to confirming the extent of margin in the specimen[2]. To confirm the extent of margin in the specimen, a highly focus X-ray source is required which can easily detect microcalcifications in excised breast tissue. However, to develop a microfocus X-ray source, a small electron source is needed.

The filament-based electron gun (E-gun) produces free electrons for X-rays by heating the filament at more than 2000^{0}C. The filament has a physical limitation to an extent it can be made smaller and still can be used as electron source. Thus, conventional filament-based microfocus X-ray tubes are equipped with different kind of coils to produce narrow view of electron inside the vacuum. However, cold or field emitters such as Carbon nanotubes (CNT)s can be used as an electron source even if it is a size of few micrometers. Thus, CNT-based electron emitters are suitable candidate for developing an easier and better microfocus X-ray source. Recently, a paper was published by Li's group, where they showed that a CNT-based fully sealed X-ray tube was able to get the resolution of 0.5 µm without using solenoid coils[3]. When a CNT-based fully sealed X-ray tube was combined with solenoid coils, it was able to get the nano resolution[4].

Here, we report a CNT-based X-ray source with high-resolution capacity, in which CNTs were grown on 7 pointed structures of a metal point emitter. CNTs were grown on metal substrate using chemical vapor deposition (CVD) system.

Medical Imaging 2021: Physics of Medical Imaging, edited by Hilde Bosmans, Wei Zhao,
Lifeng Yu, Proceedings of SPIE Vol. 11595, 115953J · © 2021 SPIE
CCC code: 1605-7422/21/$21 · doi: 10.1117/12.2582087

Using the point emitter, an electron gun was assembled and inserted in the 2.75 inch circular cubic chamber with ion pump connection. An electron gun with focuser connected to it was designed for this X-ray source to provide a better resolution. The X-ray source presented here, will be used in intraoperative specimen radiographic system (as seen in figure 1, which is being developed by CAT Beam Tech Co., Ltd.

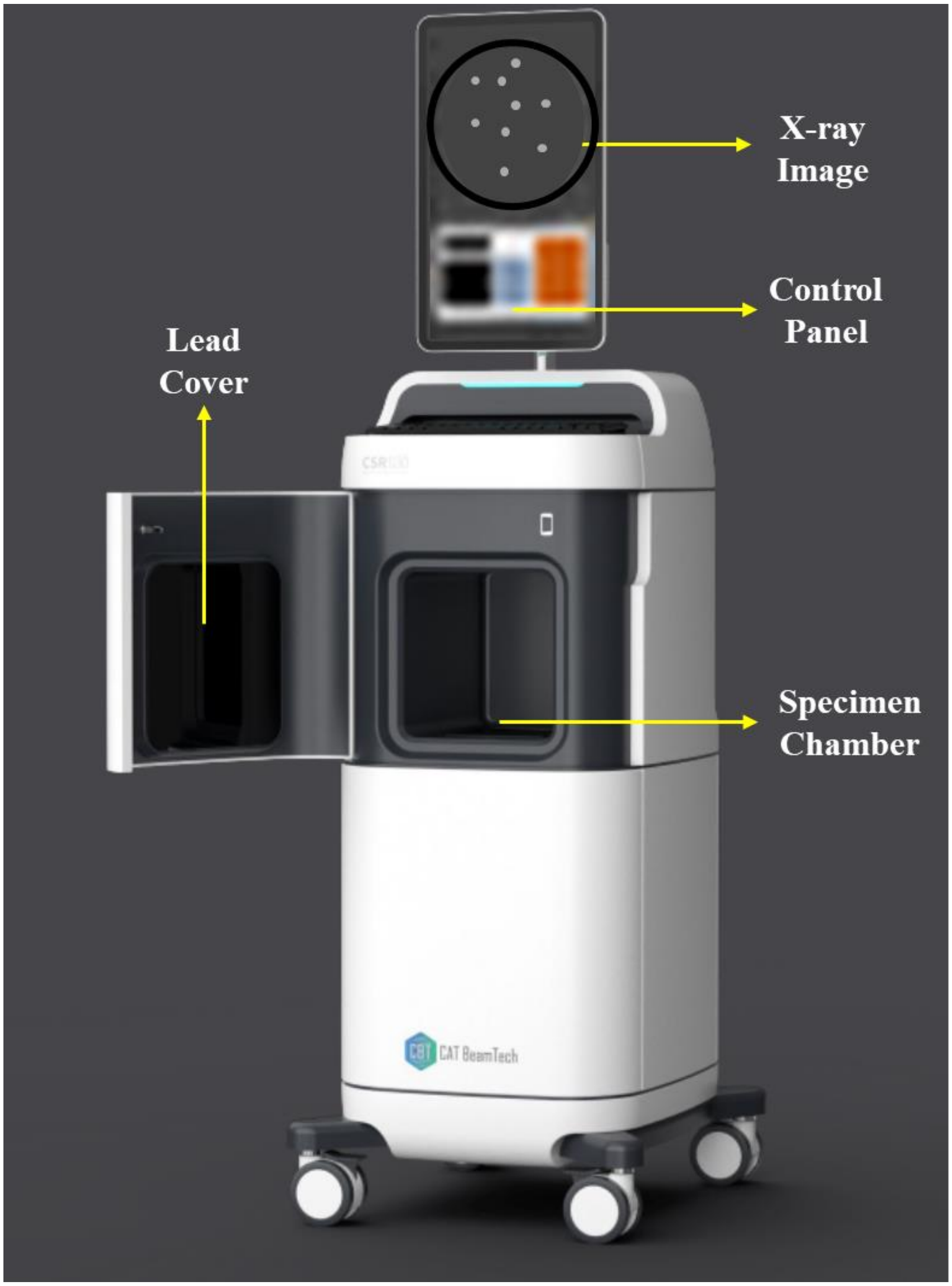

Figure 1: A 3D rendered diagram of intraoperative breast specimen system, which is being developed at CAT Beam Tech. Co., Ltd.

2. MATERIALS AND METHODS

2.1 Fabrication of 2.75 inch X-ray source.

Figure 2 (A) and 2 (B) show schematic diagram of circuit connection and optical image of X-ray source. As shown in the Figure 2, X-rays are directed downward where object to be imaged is kept 20 cm away the source. The object is placed right above the X-ray detector, so that the maximum resolution can be achieved during X-ray acquisition. The distance between anode and gate was maintained at 20 mm. The anode and E-gun was horizontal to the ground and the X-ray produced were reflected towards the ground through Aluminum (Al) window of thickness 2 mm. Al window was preferred over the Beryllium (Be) window because Be windows are expensive and difficult to handle. The specification for the system was 50 kVp with maximum anode current of 1mA. To achieve the vacuum inside the chamber, ion pump was installed on the top of the chamber and it was connected to turbo pump and rotary pump. Once the pressure inside the chamber reached the 10^{-8} torr using the ion pump, the X-ray source was detached from the turbo pump and after that it could acts as a portable X-ray source. Once could also wish to turn of the Ion pump while not using the X-ray. As it only takes 20 mins for an ion pump to get back to 10-8 torr after restarting.

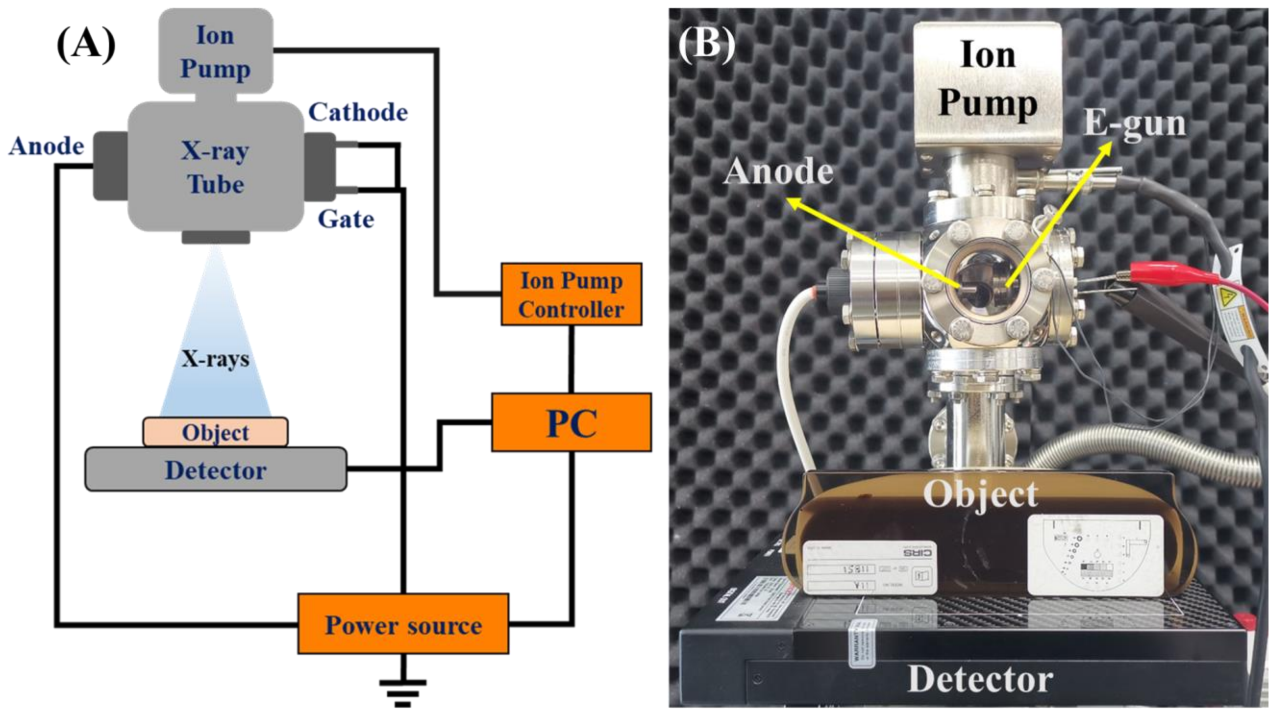

Figure 2: (A) Schematic of circuit connection of the X-ray system. (B) Optical image of the X-ray source with object and X-ray detector

2.2 Fabrication of E-gun for X-ray source

The E-gun shown in the figure 3 (A) was assembled and brazed inside the high vacuum furnace. Normally, in field emitter-based E-gun the focuser and gate are separated. However, in the present study, the honeycomb structured meshed gate and focuser was attached to each other during assembly for easier design and self-focusing structure. All together of 7 pointed structures was there in the point emitter which measured 2.7 mm from end to end. The thickness of the emitter substrate was 0.1 m and hence the total emission area was 0.0027 cm^2. The distance from the gate to cathode was 300 μm. The commercially available computer simulation software called CST was used for predicting the electron beam trajectory of an X-ray source. The simulation was performed by setting the voltages of gate and focuser at 1 kV. The tungsten anode was kept at 40 kV and point emitter used as cathode was grounded at 0 V. The simulation results showed that a highly focused electron beam of high energy was concentered on a very small area of anode surface (see Fig. 3 (F) shown in red circle). During simulation many parameters where changed such as thickness of gate electrode, length of the focuser, distance between gate to cathode and gate to anode. After all the simulations, the optimized thickness for gate mesh was 0.1 mm.

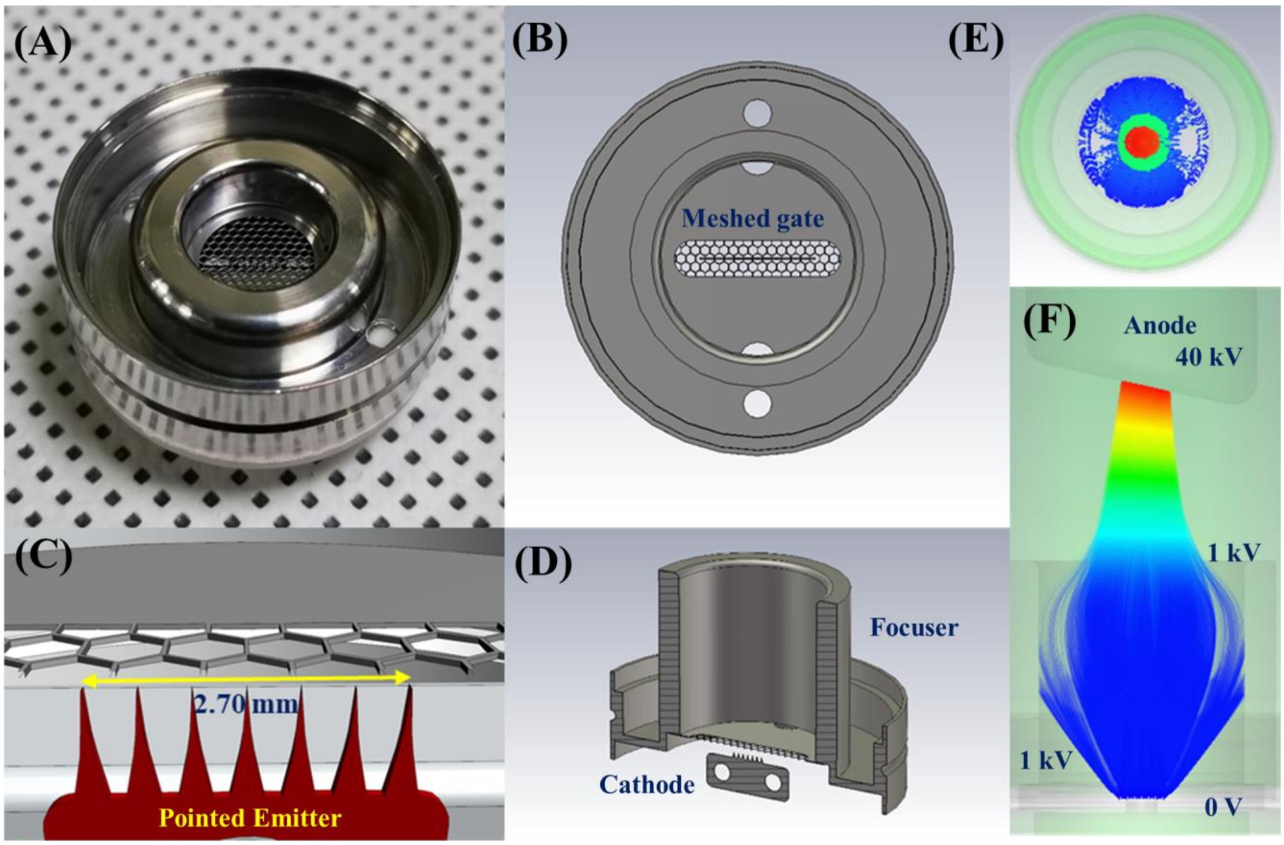

Figure 3: (A) Optical image of E- gun with focuser. 3D rendered top view of E-gun (B), image of an emitter with 7 pointed structures (C) and cross-section view of E-gun (D). CST electrostatic simulation; focused electron beam at anode (E) and electron trajectory of E-gun when cathode is at 0 V, gate and focuser is at 1 kV and anode is at 40 kV (F).

2.3 Fabrication of CNTs on Point Emitter

The metal substrate was etched into pointed structure before growing the CNTs. Using Chemical vapor deposition (CVD) system with 7:3 ratio of NH_3 and C_2H_2 gas mixtures at 920^0C, CNTs were grown on pointed structures of point emitter made up of Ni alloy with composition of Ni 42%, Cr 5%and Fe balance[1]. The average length of CNTs were 20 μm and had thickness of 60 - 70 nm. As seen in the figure 3 (A) the distance between the pointed structures was 450 μm and the effective length of each pointed structure was 500 μm. The gap was maintained between the pointed structures to reduce the screening effect under the electric field during field emission process. Figure 3. (B) shows the high resolution SEM image of point emitter taken at 1800 ×. One can see that dense forest of randomly grown CNTs were present all over the metal surface. Normally, the CNTs at the top of pointed structures take part vital role in electron emission than those grown at lower region[5]. This is due to the fact that the under the influence of electric field only the CNTs which are near to gate mesh produce maximum electrons while CNTs on the lower region need more higher electric field or applied voltage to participate in electron production inside the vacuum .margin

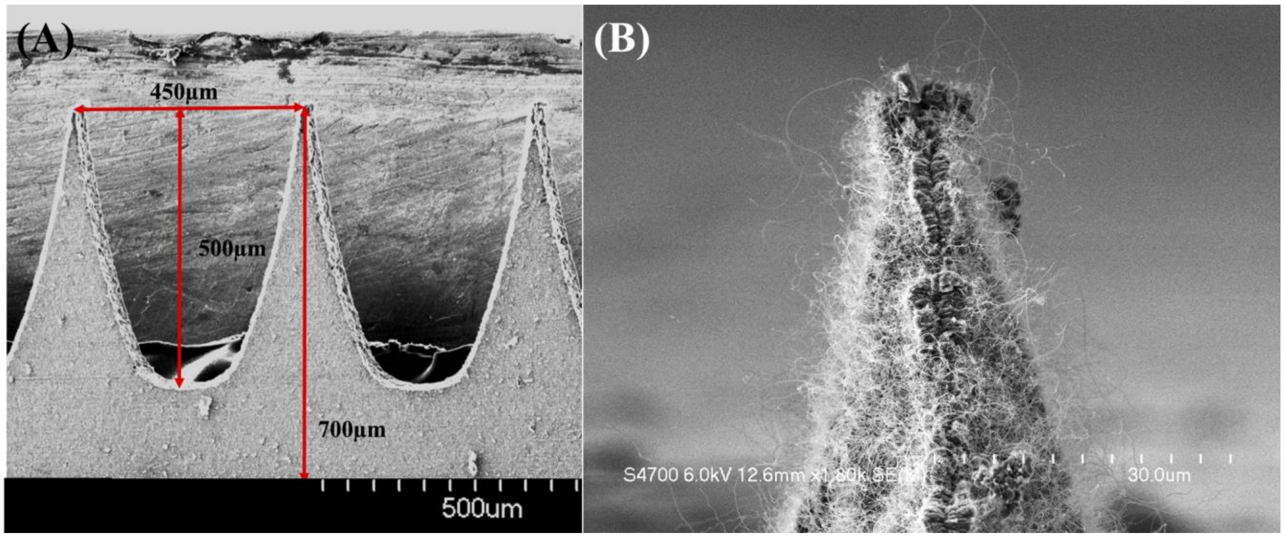

Figure 4: (A) Low magnification SEM image of point emitter with 3 pointed structures. (B) High magnification SEM image of point emitter with randomly grown dense CNTs on the top.

2.4 X-ray Image Acquisition

The X-ray image was obtained inside the lead covered X-ray use permit room. The anode and gate voltage was remotely operated outside the room. The anode voltage was accelerated to 30-45 kV with an anode current of 0.3 – 0.5 mA switched on 2secs. The gate voltage was operated from 800 -950 V exposition time of 3 sec. As mentioned earlier, the X-ray emissions were transmitted through a downward aperture. CMOS flat-panel detector (1215A, Rayence, Republic of Korea) with a CsI:TI scintillator was used as a X-ray Detector. The detector has 2352 × 2944 pixels with a pixel pitch of 49.5μm, giving an active area of 116.4 × 145.7 mm^2 .

3. RESULTS AND DISCUSSION

3.1 Field Emission Characteristic of CNT emitters

Figure 5(A) shows the field emission characteristic of CNTs point emitter. The cathode current of approximately 1.3 mA and anode current of 1 mA was obtained at a gate electric field of 3.5 V/μm. the current density as high as 500 mA/cm^2 was achieved. The high current density of the point emitter was due to spacing between pointed structures which reduced the screening effect and increased the edge effects in the emitter[6]. The anode current was measured by regulating the gate voltage in direct current (DC) mode. The leakage current ratio was below 20%. Figure 5(B) illustrates the stability of the CNT emitter for 18 hrs in DC mode. The initial cathode current was 0.6 mA at gate electric field of 3.25 V/μm. During the stability test, the current decreased from 0.6 mA to 0.5 mA, due to sudden increase in the pressure inside the chamber. However, once electrical aging process started, the current remained stabled afterwards where the maximum current was 0.75 mA, and minimum current was 0.63 mA. During both tests, the anode voltage was fixed at 5kV

At around 7^{hr} of the stability test, the anode current dropped drastically. It was not because of the sudden arcing; the reading error took with in the recording program. Right after the program was restarted, under the influence of electric field the CNT emitters on top of the point emitter started to rise and so does the increase in current. The high current and robust stability performance of the emitter signifies that the CNTs on point emitter could be the idle emitter for specimen imaging.

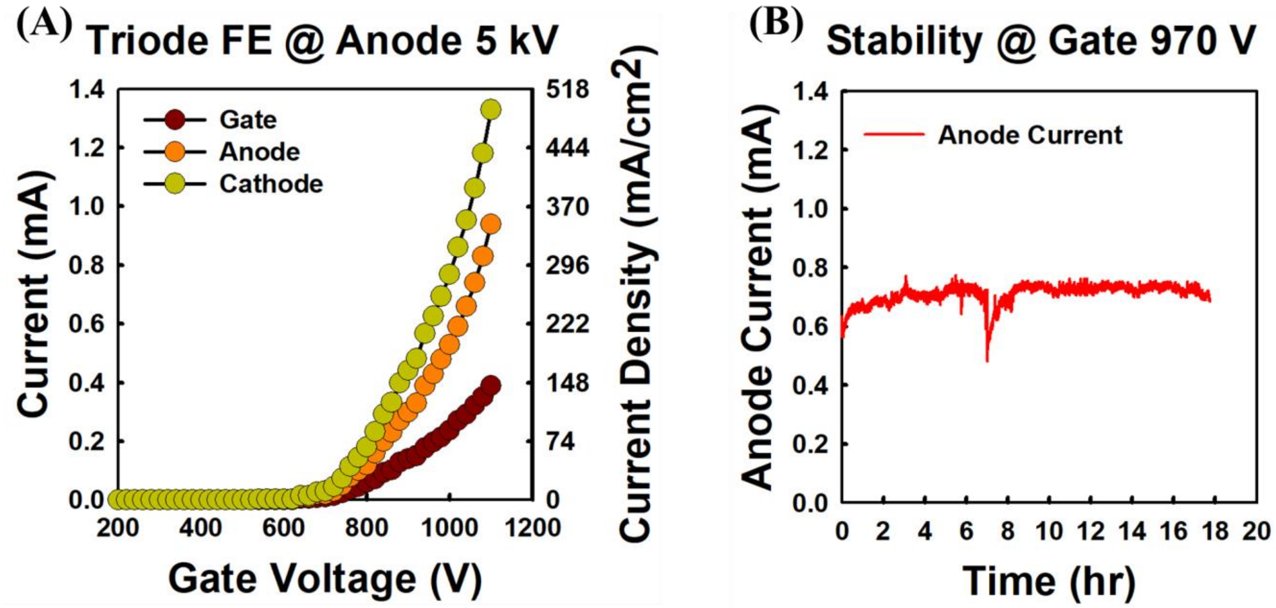

Figure 5: (A) Field emission characteristics of CNTs on point emitter e-gun. (B) Stability of E-gun at gate voltage of 970 V.

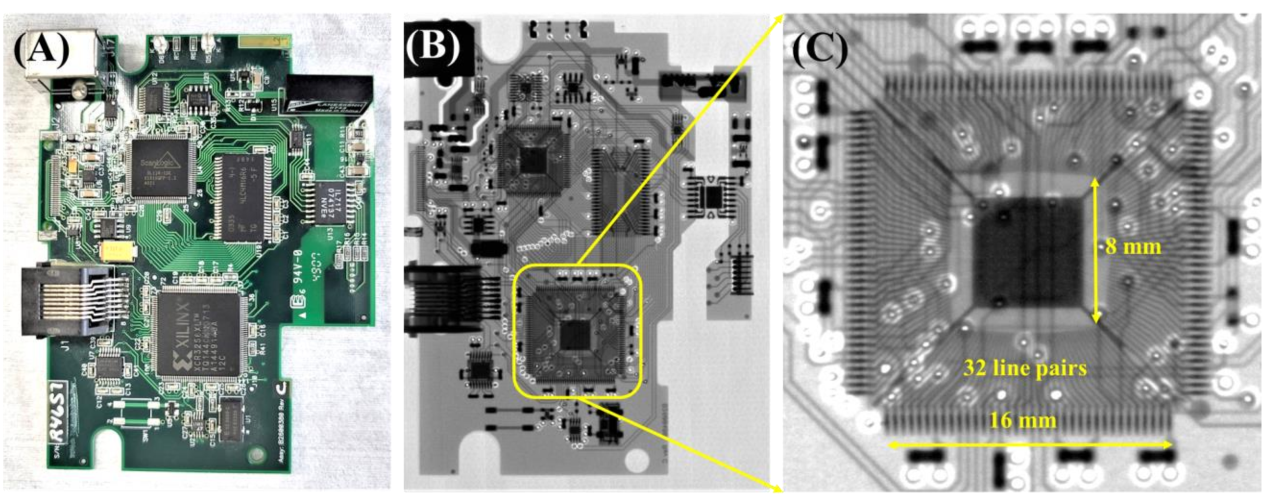

Figure 6: (A) Optical image of PCB Circuit board. (B) X-ray image of PCB circuit board at 40 kV exposed for 1mAs. (C) The magnified image of IC from the PCB circuit board to measure the resolution of X-ray source.

3.2 X-ray image of Printed Circuit Board (PCB)

Using the CNT-based point emitter X-ray source, the X-ray image of PCB (as seen in figure 6 (A)) was acquired at anode voltage of 35 kV with anode current of 0.5 mA with exposure time of 2 sec. Figure 6 (B) shows the X-ray image of PCB with IC circuits. As one can see, the circuit's lines are seen very clearly. Figure 6 (C) shows the magnified X-ray image of IC from the PCB. Again, we can see that the fines lines of IC can be seen easily. To quantify the resolution power of X-ray source, 36 line pairs in 8 mm could be seen very clearly in the magnified image. The

4. CONCLUSION

We showed that the using CNT-based E-gun, a micro-focusing X-ray source could be made. The X-ray source was built for the intraoperative specimen radiographic system. The further study should be focused on decreasing the length of point emitter to make smaller electron source. Moreover, to make the X-ray system lighter and compact, the ceramic or glass X-ray tube should be made instead of a X-ray system with ion pump. In this study, we demonstrated the working of a 2,5 inch compact open-type X-ray system with CNT point emitters. The high current density and robust stability performance in DC mode make the proposed CNT-based X-ray source a suitable candidate for intraoperative specimen radiographic system.

ACKNOWLEDGEMENT

This work was supported by the Bio & Medical Technology Development Program of the National Research Foundation (NRF) funded by the Ministry of Science & ICT (NRF-2018M3A9E9024942, NRF-2016M3A9E9942010), the Creative Convergence Research Program funded by the National Research Council of Science & Technology (CAP-18-03-ETRI) and a grant of the Korea Ministry of SMEs and Startups (1425136392).

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