Carbon nanotubes based photocathodes for multisource X-Ray generators

J.-P. Mazellier*, P. Legagneux*, L. Gangloff*, F. Andrianiazy*, S. Xavier*, P. Ponard**, N. Martinez**

* Thales Research & Technology, 1 avenue Augustin Fresnel, 91767 Palaiseau Cedex, FRANCE
** Thales Electron Devices, Zone Industrielle Vongy, 74200 Thonon-les-Bains, FRANCE

ABSTRACT

We present here our work on vertically aligned carbon nanotubes co-integrated with silicon photodetectors to produce laser controlled electron emitters, namely CNT photocathodes. The co-integration scheme has been improved and On-Off ratio up to 23 have been demonstrated on our photocathodes. These new cathodes have been integrated in a dual X-ray source where only one high voltage is required as the individual X-ray flux are controlled by laser.

Keywords: carbon nanotubes, field emission, photocathodes, modulation, X-rays

1 INTRODUCTION

Cold cathodes are promising electron sources to replace thermoionic cathodes currently used in electronic vacuum tubes (traveling wave tubes, X-ray tubes, …) . They present many advantages compared to thermoionics cathode: compact, low weight, less power consumption and low heat generation, easier modulation. The use of carbon nanotubes (CNT) as field emitters for cold cathode has generated lot of attractiveness around the world because of their unusual properties. Growth of vertically aligned CNT has been achieved by many groups and field emission up to 100µA [1] for individual CNTs has been demonstrated.

Futhermore, CNTs can be grown on microelectronics compatible substrates. This allows to integrate electronics function directly coupled to CNTs field emitters to obtain "clever" cold cathode.

Such cathode can be integrated in new type of X-ray tubes where modulation of the emitted current in the tube has to be modulated easily. X-ray tubes with such ability can be integrated in multi-source system for X-ray tomography purposes such as computed tomography scanner for medical or non destructive test applications.

2 CNT BASED PHOTOCATHODES

2.1 Vertically aligned CNT array growth

For CNT growth, we use nickel catalyst. This catalyst is patterned as an array of pellets, 7nm thick with diameter of 1µm. Each pellet is placed at the node of an array with spacing ranging from 20µm to 10µm. The array is circumscribed in a 1mm diameter circle. Under each nickel pellet withstands a TiN layer that acts as electrically conductive diffusion barrier in order to avoid Ni silicide formation (with underlying silicon substrate) which does not catalyze the CNT growth.

The subsequent CNT growth is performed in an Aixtron "Black Magic" Plasma Enhanced Chemical Vapor Deposition (PECVD) system. Scheme of the process is presented on Figure 1-a. The nickel is annealed at 600°C which causes its dewetting. Then the temperature is increased up to 700°C and a C_2H_2/NH_3 gas mixture is introduced in the chamber. A plasma is ignited by a microwave generator. The carbon of acetylene molecules is dissolved in the nickel particles. When the saturation is reached, carbon precipitates at the nickel particles edges to form graphitic planes which, by accumulation, produce the carbon nanotubes. Ammonia is used in order to selectively etch amorphous carbon phases. By this method we obtain an array of vertically aligned CNTs (VA- CNTs) as shown on Figure 1-b. The Ni catalyst clusters are present at the apex of the CNTs.

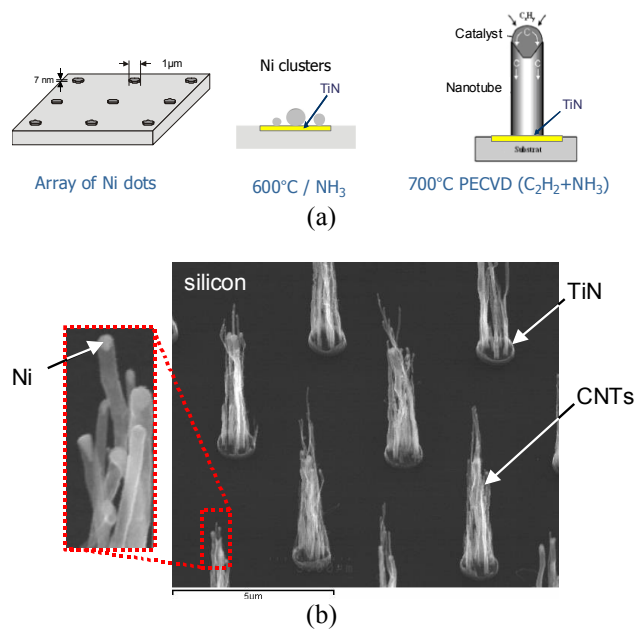

Figure 1. (a) CNT growth scheme; (b) SEM picture af VA-CNT array.

2.2 Photomodulation principle

Considering CNT cathode, underlying silicon substrate provide the electrons that are emitted into vacuum by CNTs

under extraction electrical field. In order to modulate the emitted current, one can modulate the extraction field through modulation of the anode-cathode voltage drop. But in X-ray tubes, this voltage is typically in the range 70-140kV. Modulating such high voltages can induce harsh technological issues. Futhermore, when multisources are required, each source must have its own high voltage generation to be modulated which significantly increases the integration cost and complexity.

An other way to modulate the emitted current, is to directly modulate the flow of carriers from the substrate to the CNTs. This can be done thanks to active components such as photodetectors or transistors for instance. By inserting an active component in series with CNT, while keeping the extraction voltage constant, the emitted current is limited by the current that can flow through the component. In case of transistors, the command is electrical which means that insulation to high voltage must be incorporated. Furthermore, in case of an array, phase match must be carrefuly controlled for good modulation. On the other hand, a photodetector (PD) current level can be easily controlled by a laser light flux that can be modulated. This means nor need of electrical insulation neither phase match issues. That is the reason we focused on CNTs array coupled to PD array (Figure 2) to produce CNT photocathode in order to produce modulable current for X-Ray sources.

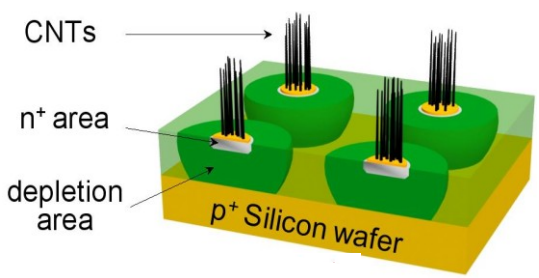

Figure 2. Scheme of CNTs-Si photodiodes array constituing the photocathode

2.3 Silicon photodiodes process flow

We used silicon based technology in order to produce our CNT photocathode. Firstly because silicon PD are widely studied and secondly because silicon can sustain CNT growth process.

Our group has already demonstrated CNT photocathode based on silicon photodiodes to work [2]. The process flow is schemed on Figure 3 with following steps : (1.a) the base substrate is bulk silicon heavily p-doped to form the negative contact of a p-i-n diode; (1.b) a 3 to 5µm thick intrinsic or lightly p-doped layer is epitaxied on the substrate; (1.c) a bi-layered resist is patterned at each node of the array; (1.d) phosphorus is implanted in windowed resist in order to form the n+ top contact; (1.e) 15nm of TiN are sputtered on the wafer, then 7nm Ni are evaporated; (1.f) the bi-layer resist is lifted-off in order to obtain the delimited photodiode array.

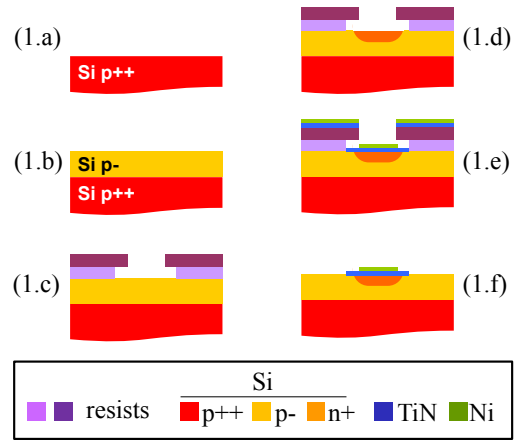

Figure 3. Technology #1: process flow

In order to control the quality of our photodiodes, dark I(V) characteristics have been measured. Considering the size of the contact, classical probe station are not suitable for this test. We used a conductive AFM in order to obtain dark IV characterics of individual photodiodes of 1µm diameter. This setup allows to locate the diode with the TiN/Ni topography during XY tapping scan. Then the tip is contacted to the metal and the voltage between the tip and the substrate is swept, measuring the current flowing in the tip at the same time.

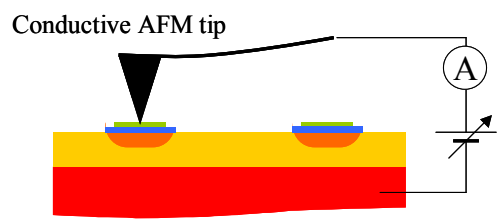

Figure 4. Conductive AFM setup for individual photodiode characteristics measurement.

Results are presented on Figure 6 for different photodiodes measured on the same chip.

A large dispersion in IV characteristics for devices processed on the same array has been observed (see Figure 6, only 2 devices IV have represented for clarity). This can be attributed to the implementation of our technology. The implanted zone is mainly delimited by the top resist window. But TiN, which is sputtered, can cover the area corresponding to the down resist window. Thus TiN contacts both the implanted zone and a part of the non implanted silicon top surface (see Figure 3). This can induce early breakdown at the surface and high leakage current levels. In order to avoid this overlapping, we have developped a new approach based on multiple e-beam lithography levels. This process is described on Figure 5.

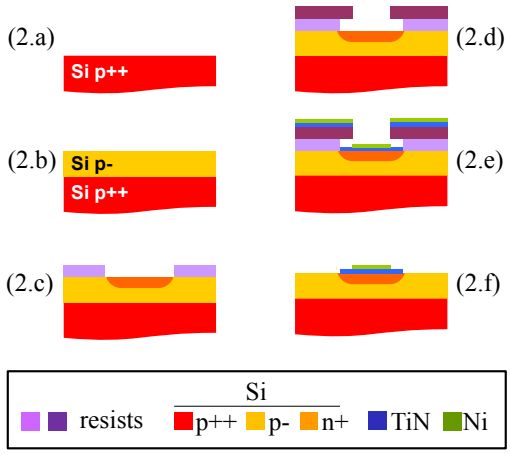

Figure 5. Technology #2: process flow

The main steps are : (2.a) Si p++ substrate; (2.b) 3-5µm thick Si p- epitaxied on substrate. Metallic alignement marks are deposited on silicon surface; (2.c) a dedicated e-beam level is used in order to define precisely the n+ top contact of each diode; (2.d) an other specific e-beam level is used to pattern a bi-layer resist in order to insure that the opened window does not exceed the n+ contact; (2.e) the TiN/Ni stack is deposited; (2.f) final lift-off is performed. This method insures that TiN/Ni stack is circumscribed in the top n+ contact. We checked that this new method increases the performances of our photodiodes as demonstrated on Figure 6.

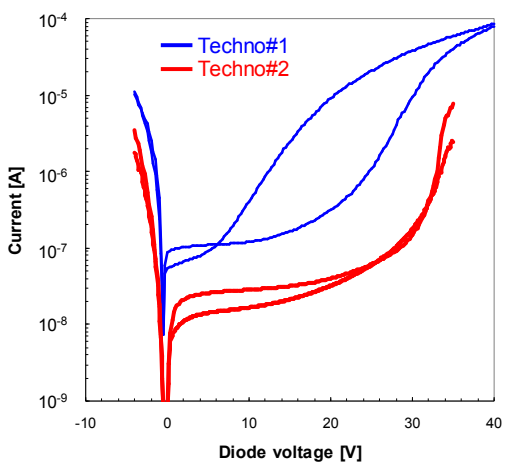

Figure 6. Dark I vs. V characteristics for technologies #1 and #2. Different curves for the same technology correspond to different devices of this technology, measured on the same array for a given technology.

We observed a significant enhancement both in reverse current level and in breakdown voltage value. The new photodiode technology is thus demonstrated to be more suitable for photocathode production.

2.4 CNT photocathode results

A typical IV characteristics of CNT photocathode is presented on Figure 7. The characteristics is dependent on the quantity of light impinging the photodiode array as expected. This allows to modulate the emitted current by light flux control while keeping constant the extraction voltage. A On-Off ratio of 23 has been measured for a On current of 300µA.

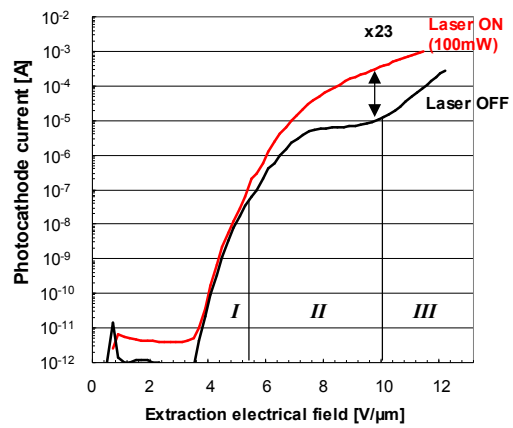

Figure 7. Photocathode characteristics in dark mode (laser OFF) and illuminated mode (Laser ON). In dark mode, 3 regimes are observed. (I) cathode limited; (II) PD limited – reverse regime; (III) PD limited – avalanche regime. ON-OFF ratio up to 23 are measured at I_{on}=300µA.

One can also notice the presence of three regime in the Off curve (Figure 7). For low currents (I), the photodiodes have no effect because their reverse current is higher than the emitted current. Then the emitted current reaches the level of reverse current of the photodiodes: these last one become the limiting part (II) and control the available emitted current. Then photodiodes enter their avalanche regime (III) and the emitted current increases significantly.

3 MULTIPLE X-RAY SOURCE

3.1 Dual X-ray source prototype

Our photocathodes have been integrated in a dual X-ray source specifically designed for CNT photocathodes. A scheme of the tube is depicted in Figure 8-a. Both photocathodes are polarized at same high voltage level by a common generator. Each photocathode can be independently illuminated by dedicated laser source and are placed in front of a tungsten anode. The emitted current, accelerated by high voltage, impacting this anode create a X-ray flux. Thus this tube create two X-ray fluxes with different origins. Each X-ray flux level is correlated to the

current level, thus to the corresponding laser flux level. A photograph of the cathode holding system and illumination system is presented on Figure 8-b.

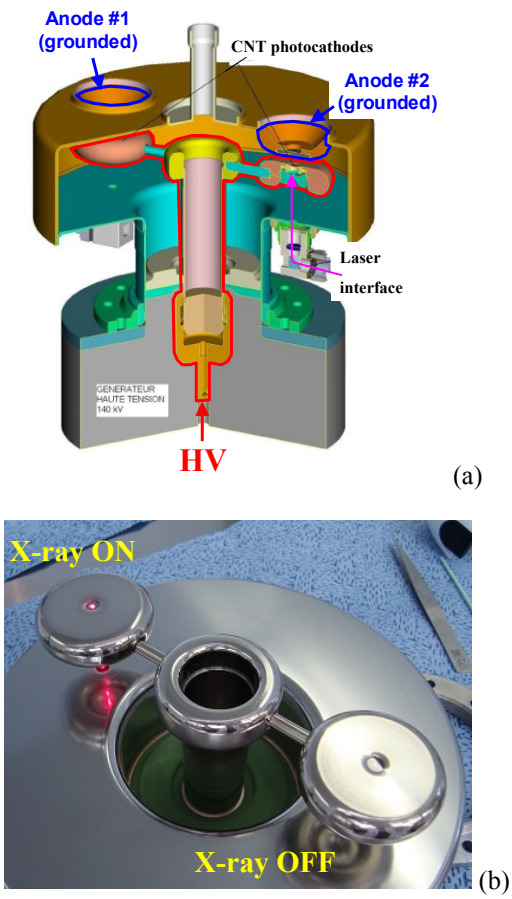

Figure 8. Dual X-ray source prototype (a) scheme and (b) photograph of the cathode holding system (High Voltage – HV- polarized) and laser illumination.

We have performed X-ray imaging of different elements thanks to this prototype. When the two laser are On, the dual-source offers a stereoscopic view of the inspected item with fine details (Figure 9). Furthermore, the stability of the image is of high quality, directly benefiting from the stability of the emission current of CNT cold cathodes.

4 CONCLUSION

We have proven that CNT cathode can be transformed into CNT photocathode by integrating photodetectors coupled directly with the CNT field emitters. The integration scheme of both elements has been improved in order to obtain good On-Off dynamics via external laser control. Such CNT photocathodes have been successfully integrated in a new type of X-ray tube where only on high voltage source is required, the X-ray flux level of each source being individually controllable by laser.

This open the way to static X-ray tomography system with multiple sources. The multi-point of view would allow, as in dynamic scanners to obtain 3D X-ray images with no mechanical part and high throughput.

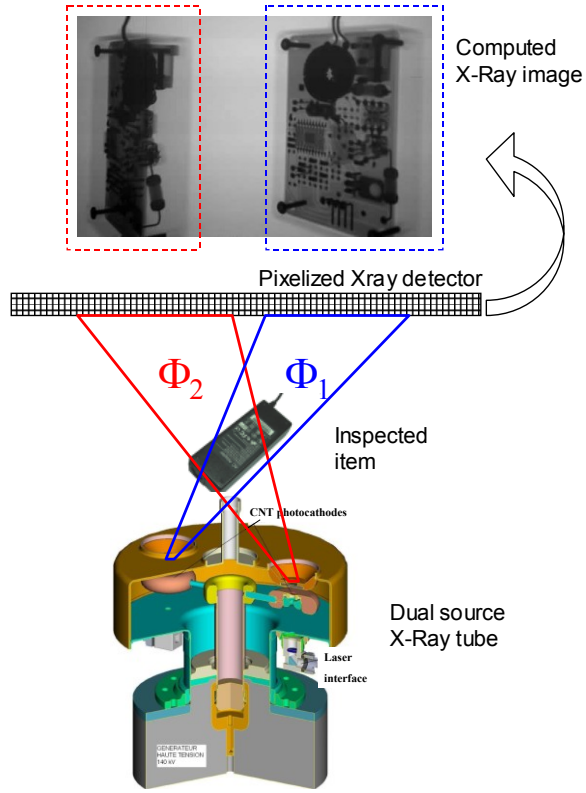

Figure 9. Stereoscopic X-ray view of a laptop power transformer.

AKNOWLEDGMENT

This work has been performed in the frame of the ANR Project Spiders and the European Project Technotubes.

REFERENCES

[1] M. Chhowalla, K. Teo, C. Ducati, N. Rupesinghe, G. Amaratunga, A. Ferrari, D. Roy, J. Robertson and W. Milne, Journal of Applied Physics, 90, 5308-5317, 2001.

[2] L. Hudanski, E. Minoux, L. Gangloff, K.B.K. Teo, J.-P. Schnell, S. Xavier, W.I. Milne, D. Pribat, J. Robertson, P. Legagneux, Nanotechnology, 19, 105201, 2008