Carbon film deposited collector electrode for high efficiency TWTs

Suneeta Arya\textsuperscript{1}, A Mercy Latha\textsuperscript{1,2,*}, S K Ghosh\textsuperscript{1,2}, Vishnu Srivastava\textsuperscript{1,2}, A K Paul\textsuperscript{3}, Monika Singla\textsuperscript{3}, Ramanand\textsuperscript{1,2} & R K Sharma\textsuperscript{1,2}

\textsuperscript{1}CSIR-Central Electronics Engineering Research Institute, Pilani 333 031, India
\textsuperscript{2}Academy of Scientific and Innovative Research (AcSIR), New Delhi, India
\textsuperscript{3}CSIR-Central Scientific and Instrumentation Organization, Chandigarh 160 030, India

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Collector plays a vital role in determining the overall efficiency of a TWT. Higher efficiency in helix TWTs for satellite applications is one of the stringent requirements. For the enhancement of collector efficiency, various techniques are employed like (i) multi-stage depression, (ii) use of electrode material with low secondary electron emission co-efficient, (iii) texturing of electrode inner surface etc. As the carbon exhibits low secondary electron emission properties, it is a favourable material for the collector electrodes of high efficiency TWTs. Either high density graphite or the OFHC copper coated with carbon film can be used as collector electrodes of high efficiency TWTs. In order to coat carbon on OFHC copper electrodes, a suitable \textit{RF} sputtering system has been developed. Various process parameters have been optimized in order to get desired carbon film deposition on OFHC copper collector electrodes. Carbon film deposition on OFHC copper has been accomplished and characterized for the suitability to use in the multi-stage depressed collector. This paper presents the details of \textit{RF} sputtering system developed, carbon film deposition process parameter optimization and characterization of carbon film deposited on OFHC copper sample.

**Keywords:** Carbon film deposition, Collector electrodes, High efficiency, Multi-stage depressed collector, \textit{RF} sputtering, Secondary electron emission coefficient, TWTs

\section*{1 Introduction}

Higher efficiency is among the prime requirements of space TWTs in addition to long life, high reliability, low mass and small size. Collector plays an important role in enhancing the overall efficiency of microwave tubes in general and space TWTs in particular\textsuperscript{1,4}. Efforts are made to develop the collector with highest efficiency possible, particularly for satellite communication applications\textsuperscript{5}. Various techniques are used to enhance the collector efficiency such as (i) multi-stage depression\textsuperscript{2} (usually 3-4 stages), (ii) using electrode material with low secondary emission coefficient\textsuperscript{3,6,7}, (iii) using asymmetric geometry of electrodes\textsuperscript{4,8,9}, (iv) using asymmetric magnetic field in the collector region\textsuperscript{2} etc. In addition to having material with low secondary electron emission property, it should also possess properties like UHV (ultra high vacuum) compatibility, high electrical and thermal conductivity. Because of good mechanical, electrical and thermal properties, OFHC copper has been widely used for collector electrodes. However, it has a relatively higher secondary electron emission coefficient as compared to other materials like graphite, titanium carbide (TiC), carbon\textsuperscript{7} etc. TiC coating has a disadvantage of low electrical conductivity, whereas carbon coating has good thermal and electrical conductivity\textsuperscript{10}. Alternatively, either high density graphite or OFHC copper impregnated graphite can be used as collector electrode material due to low secondary electron emission properties. But, there is technical difficulty in brazing the graphite electrode with alumina ceramic insulators. Hence, carbon film deposited on OFHC copper collector electrodes is widely used. By using carbon film deposition, the secondary electron emission coefficient of the OFHC copper collector electrodes can be reduced to a value\textsuperscript{7} of \textasciitilde0.4 from \textasciitilde1.0.

Carbon film can be deposited on the OFHC copper electrodes by sputtering. Sputter deposition is the method of depositing thin films by sputtering, i.e., by eroding the material from the target, which then deposits onto a substrate (over which the deposition was required). Depending on the type of targets and thickness of the films required, the sputtering technique can be either \textit{dc} or \textit{RF}. In \textit{dc} sputtering, the \textit{dc} potential is applied in parallel plate geometry

\*Corresponding author(E-mail: amercylatha@gmail.com)
across the two electrodes (substrate and target) in a process chamber at a low pressure (~10\(^{-2}\) mbar), and glow discharge is obtained.

The \(dc\) sputtering system has the several disadvantages as compared to \(RF\) sputtering namely, (i) requires operation at high pressure and (ii) the target or substrate cannot be insulators since charge accumulation occurs effectively stopping the process of sputtering. Hence, for carbon film deposition on OFHC copper electrodes, \(RF\) magnetron sputtering system has been developed.

2 Experimental Set-up

The general set-up of the \(RF\) sputtering system is shown in Fig. 1. The material to be sputtered is made as sputter target. The sample, which needs to be coated, is placed on substrate holder, which is heated by the substrate heater. A \(RF\) signal typically of 13.56 MHz frequency is applied between the electrodes (substrate and target) and a \(dc\) bias voltage is applied to the substrate in order to improve the film deposition adherence\(^{10}\). Electrons oscillate due to varying \(RF\) field in the process chamber, therefore, the collision probability between secondary electrons and gas molecules increases which consequently increases the ionization efficiency. The ionization efficiency can further be increased by trapping electrons near the target. This can be done by superposing a transverse magnetic field \(B\) on the electric field \(E\). Under the influence of these fields, the electrons show cycloid motion and centre of the orbit drift is in a direction of \(E \times B\) with the velocity of \(E/B\). This increases the collision probability between electrons and gas molecules which enables operation at lower gas pressures of the order of 10\(^{-3}\) mbar. So the plasma can be generated at low pressure with greater ionization efficiency thereby, more contamination free film and higher deposition rate can be achieved by \(RF\) sputtering.

Generally, argon is used for the generation of plasma in sputtering system. Though argon has ionization threshold of 15.76 eV, it is widely used due to its easy availability and low cost\(^{11}\).

A \(RF\) sputtering system for carbon film deposition has been developed. This system consists of turbomolecular combination, gate valve, process chamber, dual gauge, mass flow controller (MFC), \(RF\) generator with auto matching network, \(dc\) supply, temperature monitor, process timer and cooling lines (water flow: 75 L/h at 15°C). The photograph of the system is shown in Fig. 2 and the schematic diagram of the entire system showing the arrangement of various components in the system has been highlighted in Fig. 3.

The turbo-molecular pump (300 L/s) with rotary back-up is capable of attaining vacuum in the range of \(~10^{-6}\) mbar. Compact full range Pirani and Penning gauges are used for pressure measurement. Manually controlled gate valve (4” diameter) helps in chamber isolation. The vertically mounted cylindrical process
chamber (outer diameter of 11.8\" and height of 10.24\") consists of (a) substrate holder with substrate heater (capable of heating up to 300°C), (b) magnetron-type target holder with target of high density POCO graphite (DFP-3-2) disc of 100 mm diameter and 5 mm thick and (c) shutter. The shutter is used between target and substrate during pre-sputtering so that first few atomic layers of the target are removed by sputtering thereby, cleaning the target’s surface.

Two adjustable MFCs (one for argon and other for nitrogen) are used for introducing gas into the process chamber. Argon gas is fed in a controlled manner through the MFC at a particular rate so that desired pressure (~$10^{-3}$ mbar) is achieved during the process.

$RF$ generator is capable of producing frequency of 13.56 MHz and variable output power up to 600 W maximum with output impedance 50 $\Omega$. The $RF$ is applied between the substrate and target through a matching network of input impedance 50 $\Omega$. The purpose of the matching network is to match the impedance of the $RF$ generator with the load so that the maximum power gets transferred from the $RF$ generator to the load. The $dc$ supply having variable voltages from 0 to 500 V for applying $dc$ bias voltage between substrate and the ground.

**3 Process of Carbon Film Deposition**

OFHC copper electrodes/samples are chemically cleaned and heat-treated at 700°C in H$_2$ atmosphere to remove the impurities and thereby to achieve good coating adherence. The process chamber along with substrate holder is also cleaned prior to loading the sample. After loading the sample, the process chamber is evacuated by a rotary-turbo combination to achieve a base pressure of lower $10^{-6}$ mbar.

$RF$ power is applied through matching network between the target and substrate and $dc$ bias is applied to the substrate. Initially, electrodes are covered by the shutter for pre-sputtering of the graphite target for its cleaning. After half an hour, the shutter is opened so that the sputtering process starts. The required film deposition time is set in the process timer. An image captured during the process is shown in Fig. 4.

The high energy argon ions hit the surface of the target carbon disc and surface get ejected in the form of neutral particles - either individual atoms, clusters of atoms or molecules. As these neutral particles are ejected they will travel in a straight line unless they come into contact with something - other particles or a nearby surface. As the electrode is placed over the substrate holder, in the path of these ejected particles, it will be coated by a thin film of carbon.

The operational steps involved in the sputtering process has been summarized in flow-chart (Fig. 5).

**4 Results and Discussion**

Prior to having the desired carbon film deposition on OFHC copper electrodes, a lot of experimentations in order to optimize various process parameters have been carried out on OFHC copper rectangular plate instead of actual collector electrodes.
The various process parameters like RF power, dc bias voltage, operating pressure and time, have been optimized iteratively in order to have the optimum carbon film deposition. The optimized process parameters in terms of RF power, dc bias voltage and operating pressure are presented in Table 1.

4.1 Thickness
In order to optimize the process time, the process of carbon film deposition is repeated for different time intervals on partially masked OFHC copper rectangular plates. The optimum thickness of around 600 nm has been obtained in 5 h with the deposition rate of around 120 nm/h. The thickness has been measured by using DEKTEC6M stylus surface profilometer.

4.2 Adherence
The adherence of the deposited film has been tested by rubbing and acetone degreasing of the samples. The sample has been heated in vacuum (1×10^{-5} mbar) at 600°C and the film quality remained intact.

The carbon film deposition on actual OFHC copper collector electrodes [Fig. 6(a)] and textured electrode [Fig. 6(b)] have been accomplished with the process parameters optimized.

4.3 UHV Compatibility
The UHV compatibility of the carbon coated OFHC copper electrodes have been verified using SUPAVAC residual gas analyzer with UHV processing system\textsuperscript{12}. The results of residual gas analysis at various stages (before baking, at 550°C holding for 30 h and after baking) are presented in Table 2. No unusual degassing has been observed in comparison to OFHC copper electrodes thereby validating the UHV compatibility of the carbon coated electrodes.

4.4 Secondary Electron Emission Measurement
The experimental evaluation with respect to the secondary electron emission coefficient measurement of carbon coated OFHC copper sample and uncoated OFHC copper sample have been carried out.

The ratio of the total emitted secondary electron current ($I_s$) to the primary electron current ($I_p$) is secondary electron emission co-efficient ($\delta$) as given:

$$\delta = \frac{I_s}{I_p}$$

Experimentally, it can be measured by Eq. (2) as:

$$\delta = 1 - \frac{I_p - I_s}{I_p}$$

With an electron beam focused on the sample, the measured sample-to-ground current is equal to beam current $I_p$ minus the secondary emitted current $I_s$. When an appropriate positive bias voltage (~70-90 V) is applied to the sample, resulting sample-to-ground current is equal to the total primary beam current $I_p$. The secondary electron emission coefficient of the carbon coated OFHC copper sample and uncoated OFHC copper sample has been measured by using the ErLEED optics system fitted to the Auger spectroscopy system\textsuperscript{12}. The measured value of secondary electron emission coefficient for OFHC copper and carbon-coated OFHC copper samples is shown in Fig. 7, over the energy level in the range 250-1750 eV.

For the realization of collector efficiency improvement due to reduction in SEE coefficient of collector electrodes of a typical 4-stage depressed collector (designed for Ku-band 140 W helix TWT for satellite communication) has been simulated\textsuperscript{13} using EGUN (Fig. 8). The improvement in collector efficiency using carbon deposited OFHC copper electrodes is highlighted in Table 3.
Conclusions

A RF sputtering system has been developed for the deposition of carbon film on OFHC copper electrodes of multi stage depressed collector of high efficiency helix TWTs. Process parameters in terms of RF power (200 W), dc bias voltage (40 V), operating pressure (4.0 – 5.0 × 10^-3 mbar) and duration (5 h) have been optimized for getting desired carbon film deposition thickness ~ 0.6 µm. The deposited film has been characterized for its adhesion before and after heat treatment in vacuum (up to 600°C). It remains intact. UHV compatibility through RG analysis has been found at par with OFHC copper collector electrodes. It has been observed through secondary electron emission coefficient measurement using ErLEED optics system that there is a significant reduction in the secondary electron emission coefficient value of carbon coated sample in comparison to uncoated OFHC copper, e.g., at 500 eV primary energy, the value of SEE coefficient for carbon coated sample is 0.38 while for uncoated OFHC copper sample it is 1.06. The corresponding improvement in collector efficiency due to reduction in SEE coefficient (~3.5%) is highly significant.

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