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Rapid communication

Chromium coated silicon nitride electron beam exit window

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ABSTRACT

A Si_3N_4 membrane with a thin Cr coating is proposed and demonstrated as an electron beam exit window. On average, 85% electron power transmission efficiency was achieved with a 1 μm thick Si_3N_4 membrane coated with 1 μm thick Cr and the membrane sustained a beam current of up to 3 mA at 60 keV electron energy for the continuous operation of 3 min. However, for an uncoated membrane of same thickness, the average electron power transmission efficiency was 71% and the maximum beam current sustained was 800 μA. It was also shown that a one micron thick Si_3N_4 square membrane window of 10 mm × 10 mm could withstand a differential pressure of 1.3 bars.

Electron gun accelerators are used to produce electron beams for numerous applications [1]; to produce plasma, to weld metals, to melt materials, to treat gas [2–4], to treat bio waste [5], to treat waste water [6], to modify surfaces [7] and to make micro/nano patterns on materials [8]. Many of these applications require the electron beam to be used in atmospheric pressure whereas the electron beam is generated in vacuum for any reasons such as efficient accelerating, better beam shaping, avoid plasma formation, and to protect thermionic emitters from chemical reactions. In such cases, an Electron Exit Window (EEW) is used to transfer electron beam from vacuum into atmosphere as shown in Fig. 1. A good EEW should be transparent to electrons and a strong barrier between atmospheric pressure and vacuum.

Thin film membranes (e.g.: Silicon, Silicon Nitride and Titanium) are proposed in literature and used in industry in low power applications such as TEM and SEM [9,10]. Relatively thick (up to 100 μm) Aluminium foil has been widely used in industry for high electron energy (up to 6 MeV) applications [11,12]. Reported power transmission efficiencies of the EEW are between 13% and 95%, this being mainly dependent upon the material, its thickness, and the electron energy. In the case of [11], a large Al foil window was used and the electron beam was scanned across the area and operated in pulsed mode operation (0.375 μs pulses and duty cycle is less than 1%) to avoid the thermal loading and consequence failure of the Al foil. Furthermore, a complex cooling technique was required to take the heat away from the window membrane. It was shown in [12] that Al coated polyester film improved the power transmission efficiency by a factor of two compared to just Al alone; however the duration for which the foil was exposed to the electron beam was very low (20 μs) and duty cycle was much less than 1%. Electron gun based plasma generation for flue gas treatment (e.g.: $deNO_x$ and $deSO_x$) [2,4] requires a high beam current with low electron energy in order to maintain a high dosage (e.g.: 9 kGy) in the plasma. In such cases, the power efficiency of the system was very low (<50%) mainly due to inefficient electron transmission of power through EEW. This means electron guns need to operate at more than 2× more power than actually required to compensate the power loss at EEW. This makes the plasma treatment of flue very expensive both (capital and operational) and environmentally harmful. This study is aimed at low electron energy (~60 keV) beams to generate non-thermal plasma as very low mean electron energy (1–5 eV) is only required to treat exhaust gas [13] and use of high (>1 MeV) or medium (0.5–1 MeV) electron energy is an overkill. Low electron energy would also give many other benefits, such as reduced cost in terms of capital cost (voltage supply, electron beam column and

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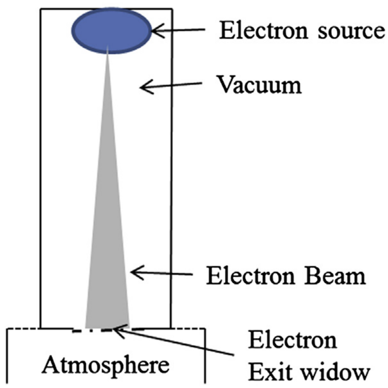

Fig. 1. Electron Beam Generation.

associated accessories) and running cost (lower electrical energy, longer life of electron source and less cooling), smaller foot print and eco-friendly. Furthermore, the absolute power loss at EEW will be much less for 60 keV than high/medium energy electron beam and therefore the required EEW cooling is much less.

The two main underlying criteria of an EEW are electron power transmission efficiency (EPTE) and the ability to withstand the differential pressure. These two criteria have opposing requirement on the thickness of a membrane; i.e.: the thinner the EEW the higher EPTE, however, lower the ability to withstand differential pressure and vice versa. The major challenge in using a thin film window is the heat generated due to electron collision with the window material. The thinner the window the better the electron transmission and hence less heat dissipation and vice versa. However, a thinner window means its thermal capacity is less and therefore the risk of damaging the material is very high.

In this paper, a preliminary study of the chromium coated Si_3N_4 EEW is reported. The major reasons for the choice of Si_3N_4 EEW were manufacturability to a fraction of a micron thickness and its superior mechanical properties. Si_3N_4 has high yield strength (14 Gpa), superior thermal shock resistance (>600 σK), good oxidation resistance, low thermal expansion (3.3×10^{-6}/K) and high temperature range (melting point: 2660K–2770 K). The limiting properties of Si_3N_4 were low thermal conductivity (5–30 W/m K) and low electrical conductivity (10^{-13}–10^{-8} S/m). High electrical conductance is needed in order to remove any accumulated charge in the membrane to ground. To overcome these challenges, Cr coating was applied to the Si_3N_4 EEW. Cr has relatively good thermal conductance (94 W/m K) and good electrical conductance (7.9×10^{6} S/m).

In this preliminary study, six Si_3N_4 membranes (LPCVD deposited silicon rich nitride) were manufactured; half of them were coated with Cr of μm thickness. A simple heat sink was also designed and adopted as a means of heat transfer from the EEW to the atmosphere. The schematic and photograph of the Si_3N_4 EEW with Cr coating and associated heat sink is shown in Fig. 2.

FEM models of the Si_3N_4 EEW (with and without Cr) coating were developed and solved in COMSOL multi-physics platform. This model was used to simulate heat transfer by conduction and radiation. The following equation of heat transfer by conduction was used to solve for temperature, T [K], in the solids.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \tag{1}$$

Where ρ density of the material [kg/m^3], C_p is the specific heat capacity [J/(kg.K)], k is thermal conductivity of the material [W/(kg.K)], and Q is heat source other than viscous heating [W/m^3]. In our case Q is the energy lost by the electron beam.

The equation governing the heat radiation (derived from Stefan–Bolzman law) to solve for temperature is;

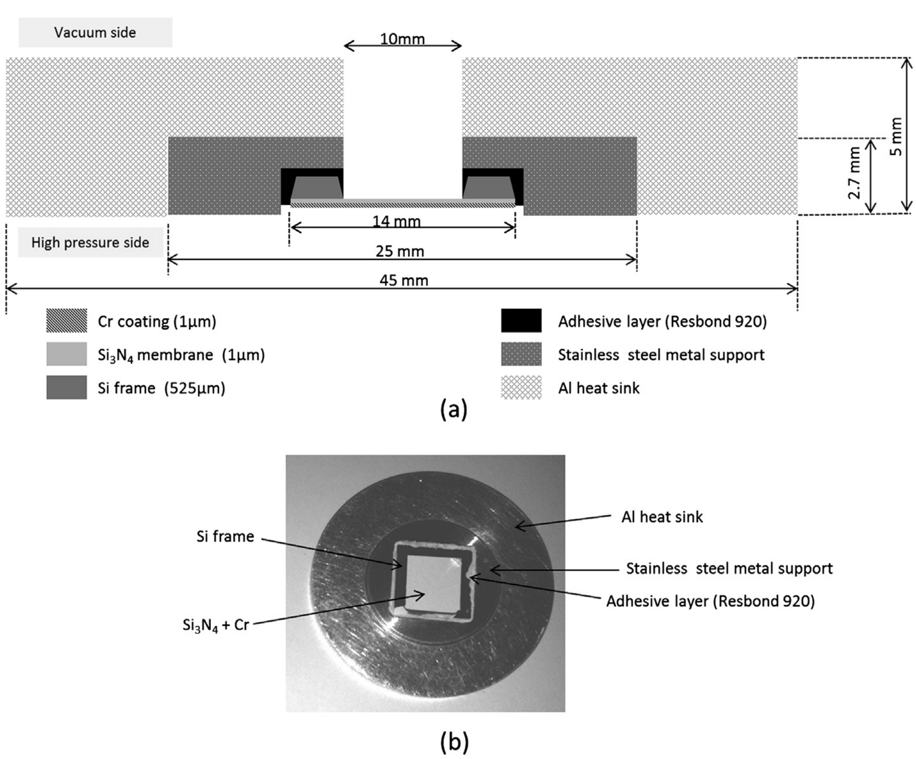

Fig. 2. Si_3N_4 EEW with Cr coating (a) 2D Schematic (b) Photograph.