A Micro Ionizer for Portable Mass Spectrometers using Double-gated Isolated Vertically Aligned Carbon Nanofiber Arrays

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Abstract—We report a gas ionizer based on arrays of micro-fabricated double-gated isolated vertically aligned carbon nanofiber (VA-CNF) for application in low power portable mass spectrometers. Field emitted electrons from vertically aligned carbon nanofibers are accelerated to high energy and subsequently collide with neutral gas molecules leading to ionization / fragmentation of the molecules. Double-gated field emitter arrays with isolated vertically aligned carbon nanofiber tips were fabricated using a photoresist planarization technique. Two types of devices were fabricated and characterized. The first device has the emitter tip in the same plane as the extraction gate and second device has the emitter tip 900nm below the extraction gate. All devices were made using a process which results in gate and focus diameters of 1.7µm and 4.2µm, respectively. When operated as a field emitted electron impact ionizer, for the same ion current, the ionization efficiency (ratio of ions to emitted electrons) increased from 0.005 to 0.05 as the pressure is increased. In comparison with electron impact ionizers based on thermionic electron sources the power dissipation reduced from >1 W to 100 mW.

Index Terms—Vacuum technology, Ionization

I. INTRODUCTION

Portable mass spectrometers (MS) require low power and compact gas ionizers. State of the art instruments use electron impact ionizers based on thermionic emission sources [1,2,3], which produce electrons from a heated filament. Thermionic electron sources consume high power, typically >1 W and hence are not suitable for portable low power mass spectrometers. In addition, the electron impact ionizers based on thermionic electron sources have slow switch-on time and are not robust. These disadvantages could be eliminated if the thermionic electron source is replaced by a cold electron source such as a field emission array. The advantage of using a field emission electron source for electron impact ionization is that field emission occurs at room temperature and does not require heating. In the field emission process, a voltage is applied between a sharp tip and a conducting gate with an annular aperture to create a large electric field at the tip apex. This applied electric field bends the vacuum level and thus narrows the energy barrier between electrons in the tip and the vacuum, leading to electron tunneling. Electrons are emitted as soon as the electric field is applied and consequently this process has a fast switch-on time. There are several other significant advantages of replacing thermionic electron sources with a field emission electron source in an electron impact ionizer [4]. These advantages include elimination of thermal cracking of delicate molecules, avoidance of outgassing due to the thermal load and most important is the significant reduction in pumping requirement due to the elimination of the hot filament.

While impact ionizers based field emitted electrons have the above advantages, they are very vulnerable to tip erosion by back streaming ions because the tip is typically biased at a lower potential relative to the extraction gate and the accelerating electrode. To reduce the vulnerability to back ion tip erosion, a second gate positioned between the extraction gate and the accelerating anode and biased at lower voltage relative to the tip, focuses the field emitted electrons and collects the back streaming ions, thus protecting the tip.

This paper presents the design, fabrication and characterization of an electron impact ionizer based on a micro-fabricated double gated vertically aligned carbon nanofiber (VA-CNF) field emission arrays (FEAs). When voltages are applied to the extraction gate and focus, the double gated VA-CNF arrays emit electrons. Ions are generated when the electron beam from the FEAs collide with neutral molecules after being accelerated to a high energy.
II. DEVICE STRUCTURE AND MODEL

The electron impact ionizer (EII) uses a double gated field emitter array as a cold electron source to reduce power dissipation. Electrons accelerated to high energy collide with neutral molecules to create ions which are fragments of the neutral molecules. The double-gated field emission array (FEA) has a second gate (focus gate) stacked above the first gate (extraction gate), as shown in Figure 1. The emitter tip is a vertically aligned carbon nanofiber (VA-CNF) that is bombarding the tip.

A. Field emission electron source

The double-gated VA-CNF array is the field emission electron source for the ionizer. It has four terminals, — emitter, extraction gate, focus and anode. It can be operated as a four terminal device in which the focus and extraction gate are biased at different voltages or it can be operated as a three terminal device in which case the focus and extraction gate are biased at the same voltage.

Field Emission Model

The emission current depends on electrostatic field (F) at the tip surface which is a function of the bias voltages applied to both gates. Thus, the emission current depends on both the extraction gate bias voltage, VG and the focus bias voltage VF. The field (F) at the tip surface is related to VG and VF through the gate field factor (βG) and the focus field factor (βF), respectively. Using superposition, the tip apex field is expressed as

$$ F = \beta_G V_G + \beta_F V_F $$

The Fowler-Nordheim (FN) equation is used to calculate the total field emission current. The FN equation approximates the electron transmission probability using the Wentzel-Kramers-Brillouin (WKB) formulation [5, 6]. Assuming the effective emitting area is α, then the emission current for the double-gate FEA (four-terminal FEA) is given by:

$$ I(V_G, V_F) = \frac{\alpha \times A}{1.1 \times \phi} \exp \left[ \frac{B \times 1.44 \times 10^{-7}}{\sqrt{\phi}} \right] \times (\beta_G V_G + \beta_F V_F)^2 \times \exp \left[ \frac{0.95 \times B \times \phi^{3/2}}{\beta_G V_G} \right] $$

(1)

where $ A=1.56 \times 10^{-6} $, $ B=6.87 \times 10^{-7} $ and $ \phi $ is the workfunction of the tip material.

When the double-gated FEA is characterized as a three-terminal FEA, the focus and the gate are biased at the same voltages, i.e. $ V_G = V_F $. In this situation, the tip apex field can be expressed as

$$ \beta_{eff} V_G = \beta_G V_G + \beta_F V_F = (\beta_G + \beta_F)V_G $$

(2)

and the field factor $ \beta_{eff} $ can be express as

$$ \beta_{eff} = \beta_G + \beta_F $$

(3)

Hence, the emission current for the three-terminal FEA is given by

$$ I(V_G) = \frac{\alpha \times A}{1.1 \times \phi} \exp \left[ \frac{B \times 1.44 \times 10^{-7}}{\sqrt{\phi}} \right] \times (\beta_{eff} V_G)^2 \times \exp \left[ \frac{0.95 \times B \times \phi^{3/2}}{\beta_{eff} V_G} \right] $$

(4)

Field Factors

To estimate the value of the gate field factor ($\beta_G$), focus field factor ($\beta_F$), and effective field factor ($\beta_{eff}$) when $ V_F=V_G $, two models with the dimensions specified in Figure 2 (a) and (b), symmetrically placed between the two annular apertures in the extraction gate and focus gate electrodes. The electrodes are both thin films of doped amorphous Si. Two silicon dioxide insulating films separate the emitter electrode from the extraction gate electrode and the focus electrode from the extraction gate electrodes. The anode is a perforated screen that will allow the extraction of the ions. When appropriate voltages are applied to the extraction and focus electrodes, an enhanced electrostatic field is created at the VA-CNF tip which leads to the extraction of electrons. The extracted electrons are accelerated by the anode towards the ionization region where the electrons collide with neutral molecules resulting in ionization. The second gate (focus) which is typically biased at a lower potential than the extraction gate serves two purposes. One function of the focus is to collimate / focus the extracted electrons. The second function of the focus is to attract and absorb back streaming ions, which reduces the chances of ions
respectively, were built in MATLAB using the finite element method (FEM). Both models have gate aperture radius of 0.85-µm and focus apertures of 2.1-µm which corresponds to the apertures we later obtained experimentally. One of the models has a tip height which is aligned to the plane of the gate aperture and the other model has the tip 900nm below the gate aperture which again corresponds to what we obtained experimentally later. In this work, nickel is used as the catalyst material to grow isolated vertically aligned CNFs and the Ni disks have a thickness of 4nm and a diameter of 250nm. A disk with these dimensions has volume of 1.96x10^-16 cm^3, which, theoretically, would form a sphere with a radius of 36nm during the anneal that occurs during VA-CNF growth. Thus, the tip radius was assumed to be 36nm for the MATLAB simulation.

The purpose of the MATLAB models is to determine how the potential applied to the two gates affect the electric field generated at the tip when the relative positions of the tip and the gate are different. From these two models, we obtained \( \beta_G = 1.19 \times 10^6 \) [V/cm], \( \beta_F = 3.07 \times 10^5 \) [V/cm], and the ratio of the field factors \( \beta_F / \beta_G = 0.272 \) when the tip is in-plane with the gate. When the tip is 900nm below the gate, \( \beta_G = 4.97 \times 10^5 \) [V/cm], \( \beta_F = 1.12 \times 10^4 \) [V/cm], and the ratio of the field factors \( \beta_F / \beta_G = 0.023 \) indicating considerable screening of the tip from the influence of the focus gate by the extraction gate.

Using the same models, \( \beta_{\text{eff}} \) as a function of the tip radius in the double-gated structure can be deduced. When the tip is in-plane with the extraction gate and \( VF=VG \),

\[
\beta_{\text{eff}} = \frac{11.2 \times 10^5}{r^{0.848}} \] [V/cm].

When the tip is 900nm below the extraction gate and \( VF=VG \),

\[
\beta_{\text{eff}} = \frac{47.5 \times 10^5}{r^{0.848}} \] [V/cm],

where \( r \) is in nanometers. These two relationships are similar but not exactly the same due to the different tip positions relative to the extraction gate [6].

**B. Electron Impact Ionization (EI) model**

In electron impact ionization, electrons are first extracted from the field emitter tips and then accelerated to an energy several times higher than the gas molecules’ ionization energies. The ionization efficiency (\( II(E)/IE(E) \)) is given by [7]:

\[
\frac{I_i(E)}{I_e(E)} = \rho \times L \times \sigma_{\text{total}}(E)
\]

(5)

In the equation, \( \rho \) is density of neutral molecules in the gas; \( L \) is the collision pathlength and \( \sigma(E) \) is the total ionization cross section.

Usually, for most gas molecules, the peak of the ionization cross section is of the order of 10^{-16} cm2.

In this work, the electron beam was generated by field emission and the electron emission current can be calculated from the Fowler-Nordheim (FN) equation [5,6]. Using Equation (5) the ion current is estimated from the number density of molecules in the gas (\( \rho \)), the collision pathlength (\( L \)), the total ionization cross section (\( \sigma(E) \)), and the electron current (\( IE \)) using equation (5).

### III. IONIZER FABRICATION

The VA-CNF arrays were designed such that the electric field generated at the tip is maximized and the shielding effect from the neighbors is minimized. Furthermore the device is capable of handling high voltages. The fabrication of the double-gated CNF structure starts with the definition of a 250nm diameter and 4nm thick Ni catalyst at each emission site with 10μm pitch by E-beam lithography and lift-off technique [10]. The catalyst size guarantees nucleation of a single Ni dot at each site [10, 11] and subsequent growth of an isolated 4μm tall VA-CNF using plasma enhanced chemical vapor deposition (PECVD) at 725ºC, as shown in Figure 3.

Once CNF was grown, the extraction gate and the out-of-plane focus gate were fabricated with a novel photoresist (PR) planarization technique and the fabrication process flow is shown in Figure 4. This fabrication process starts with the formation of the gate insulator and the gate electrode (steps A through E). A conformal layer of plasma enhanced chemical...
vapor deposition (PECVD) oxide was deposited as the gate insulator to separate CNFs and the gate material (amorphous-Si), as shown in Figure 5 (a). Next, a conformal PECVD doped a-Si was deposited on top of the oxide to form a gate electrode (Figure 5 (b)). Steps C through E illustrate the self-aligned technique. The PR was spun on the wafer at a high speed, which resulted in PR surface planarization without using CMP (Figure 5(c)). This smooth PR layer defined the structure of the gate aperture. An anisotropic silicon reactive ion etch (RIE) was then used to etch the a-Si (Figure 5 (d)) and thus open the gate aperture. By varying the etch time, we can change the tip position with respect to the extraction gate. With the less etch time, less a-Si is removed, the tip ends up below the extraction gate. In this work, two structures were made, one has the tip in-plane with the gate and the other has the tip 900nm below the gate. After the gate aperture was patterned by RIE, the PR was then removed. Figure 6 shows SEM pictures of an array of a single-gated CNF device fabrication process.

**IV. FIELD EMISSION CHARACTERIZATION**

**A. Three-terminal Field Emission Characterization**

The double-gated CNF arrays were first characterized as three-terminal field emitters with the gate and focus biased at the same voltages. To ensure the field emission data is reproducible, a series of 12 IV sweeps, which consisted of a series current-voltage measurements as the extraction gate voltage is stepped up immediately followed by a series of current-voltage measurements as the extraction gate voltage is stepped down, were performed in sequence. Anode current versus extraction gate voltage plots are shown in Figure 8 (a) for the device with tips that are in-plane with the gate and in Figure 8 (b) for the device with tips that are 900nm below the gate. Note that there is a non-zero current of 1E-11 Amp even at 0V. This is a system noise from the instrument, confirmed by a blank test without any wafer.
Rewriting Equation (4) as

\[ I = a_{FN} V_G^2 \exp \left( -\frac{b_{FN}}{V_G} \right) \]  

(8)

with

\[ a_{FN} = \frac{\alpha \beta_{eff}^2}{1.4 \phi} \exp \left[ \frac{B(1.44 \times 10^{-7})}{\phi^{1/2}} \right] \]  

(9)

and

\[ b_{FN} = \frac{0.95 B \phi^{1/2}}{\beta_{eff}} \]  

(10)

we can extract the FN parameters aFN and bFN from a plot of Ln(IA/VG^2) vs 1/VG. Figure 9 (a) and (b) show the FN coefficients (aFN is the intercept and bFN is the slope of the FN plot) with the error and standard deviation. From the FN plot we observe that the values of R are close to -1, and that the standard deviation is small.

Once the bFN and aFN values were extracted, equation (9) and (10) were used to calculate the effective field factor, βeff, and the effective emitting area, α. Assuming the workfunction of CNF is 5eV, we obtained βeff= 1.75x10^6 [V/cm] and α = 75.79 [nm2] for the device with tip that is in-plane with the gate and βeff= 5.31x10^5 [V/cm] and α = 446.95 [nm2] for tip is 900nm below the gate. Using the MATLAB models described earlier, the estimated tip radius is about 3.2nm for the device with tip that is in-plane with the gate and 13.2nm for device with tip that is 900nm below the gate. This tip radius is less than the catalyst sphere that formed form the catalyst disks used to grow the CNFs. There are several reasons why the radii of the CNFs are in reality smaller than 36nm. The Ni disks were annealed at a high temperature to form Ni catalysts prior to growth of the CNFs. During this process, silicon substrate could have reacted with Ni to form nickel silicide, resulting in loss of Ni. Another possible explanation is that Ni was lost during the CNT growth process. V. I. Merkulov attributes the loss of catalysts to two main mechanisms [15]. One is, during the growth, the ion sputtering and/or dispersion of the catalyst material within the CNF reduces the size of the nanoparticle. The other is, as the size of the catalyst decreases, the upper part of CNF becomes thinner and eventually breaks off from the tip during the growth. For the tip that is in-plane with the gate structure, the estimated tip radius of 3.2 nm is much smaller than the estimated tip radius of 13.2 nm for the tip that is 900nm below the gate structure. This suggests that there are tips that are much smaller than the average tip radius and these tips with smaller radius dominate. This is consistent with earlier literature reports Plug et al [16] and Ding et al [17] which reported a distribution of the Si tip radii and that the smaller tip radii dominate electron emission from the tips. This is explained by the exponential dependence of field emission current on the tip radius.

![Fig 8. Anode current (I_A) vs. Gate voltage (V_G) showing repeatable field emission. (a) when tip is in-plane with the gate (b) when the tip is 900nm below the gate.](image1)

![Fig 9. Fowler-Nordheim analysis of the field emission data shown in Figure 8. (a) When tip is in-plane with the gate (b) when the tip is 900nm below the gate.](image2)
B. Four-terminal Field Emission Characterization and Discussion

To characterize the array as a four-terminal device, the extraction gate and the focus gate were biased at different voltages. As indicated earlier, the tip electric field depends on both extraction gate and the focus gate for the double-gated FEA. To investigate the influence of the extraction gate and the focus gate on the emission current, the gate field factor ($\beta_G$) and the focus field factor ($\beta_F$) need to be extracted from the IV data.

To accomplish this goal, two transfer characteristics were obtained. One is the focus transfer characteristics, which shows the variation of the anode current as a function of the focus voltage with the gate voltage fixed. The other is the gate transfer characteristics, which shows the variation of the anode current as a function of the gate voltage with the focus voltage fixed. The two transfer characteristics of the tip that is in-plane with the gate are shown in Figure 10 and of the tip is 900nm below are shown in Figure 11.

To extract the gate field factor ($\beta_G$) and the focus field factor ($\beta_F$), anode current ($I_A$), gate current ($I_G$), and focus current ($I_F$) are added together to compute the total emission current. We fit the emission current to equation (1) using OriginPro 7 software package [18]. There are several uncertainties that we need to consider. The value of the tip workfunction fluctuates randomly with time and the effective emitting area $\alpha$ is only an estimate that we obtained from the three-terminal measurements. Thus, L. Dvorson suggested that instead of focusing on study the $\beta_G$ and the $\beta_F$, the ratio of the field factors, $\beta_F / \beta_G$ is more stable and serves as a reliable estimate [19]. Figure 12 and Figure 13 show the fit of the data for device that has the tip is in-plane with the gate and device that has the tip is 900nm below the gate, respectively. The same two MATLAB models described earlier are used to estimate $\beta_G$ and $\beta_F$. Table 1 summarizes these parameter estimates.

**Fig 10.** Four-terminal IV data for device with tip in-plane with the gate (a) The gate transfer characteristic ($I_A$ vs. $I_G$ at fixed $V_F$) (b) The focus transfer characteristic ($I_A$ vs. $I_F$ at a fixed $V_G$)

**Fig 11.** Four-terminal IV data for device with tip 900nm below the gate (a) The gate transfer characteristic ($I_A$ vs. $I_G$ at fixed $V_F$) (b) The focus transfer characteristic ($I_A$ vs. $I_F$ at a fixed $V_G$)
V. Electron Impact Ionization Characterization

In the EII experiment, the double-gated FEA was biased as a three-terminal device (VG=VF) while the emitters were biased at 0V. A perforated screen anode is placed right above the device (L=0.5cm) and is biased at a higher voltage (400V) than the gate voltage to accelerate electrons before impact with gas molecules. The electron pass-through rate is 85%. This is measured by applying a same voltage on the ion collector and comparing the current from the ion collector and the anode gate. Then the collector voltage is set at -1100V to collect the ions generated by EII and repel electrons. The gas used in these set of experiments is Argon.

Electron current vs. Ion current at a fixed pressure

In the EII process, electrons are first extracted from the field emitter tip and then accelerated up to an energy several times higher than the gas molecules’ ionization energy. Ionization takes place when these energetic electrons collide with gas molecules. As shown in equation (5), the ion current depends on the number of electrons and the density of the gas molecules in the chamber at fixed L and \( \sigma(E) \). In this section, we demonstrate this linear relationship by varying the electron current and the chamber pressure, which is measured by a MKS 431 cold cathode vacuum sensor.

To control precisely the chamber pressure, Argon (Ar) is passed into the chamber by a needle valve, which can precisely restrain the amount of Ar flowing into the chamber. The ion current (II) and the electron current (IS) are monitored and recorded while varying the extraction gate voltage (VF=VG). This experiment was run at different pressures: 5x10^{-7} Torr, 5x10^{-6} Torr, 5x10^{-5} Torr, and 5x10^{-4} Torr. The IV characteristics of EII at the different pressures are plotted in Figure 14 (a), (b), (c), and (d), respectively.

Electron currents and the molecular density, calculated using equation (6) at specific pressures, are plugged into equation (5) to obtain the predicted ion currents (IP). L is 0.5cm, which is the distance between the ion collector and the screen anode. The screen anode is biased at 400V, which gives us the ionization cross section of \( 1.5 \times 10^{-16} \) cm^2 for Ar^+ \cite{8}. Using these parameters, the predicted ion currents are plotted with measured ion currents in Figure 14. As the pressure increases, the ion currents increase with electron currents.

Pressure Dependence

In Figure 14, we observe that as pressure increases, ion current increases. Further, to verify the linear relationship between pressure and the ion current, ion currents (collector current) and electron current (screen/anode current) were measured at

From the fit of the four-terminal IV data, summarized in Table 1, the ratio of \( \beta_F / \beta_G \) for the device with tip in-plane with the gate is 0.26 compared to 0.02 for device with tip 900nm below the gate. The values of \( \beta_F \) and \( \beta_G \) and the ratios of \( \beta_F / \beta_G \) calculated from the MATLAB simulation for both devices are consistent with the experimental data. This result agrees with the SEMs shown in Figure 7 and are consistent with the results of by L. Dvorson et al. and L.-Y. Chen et al \cite{12, 14, 19}.

<table>
<thead>
<tr>
<th>4-TERMINAL DATA</th>
<th>Matlab Simulation</th>
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<tr>
<td>( \beta_F ) [V/cm]</td>
<td>( \beta_G ) [V/cm]</td>
</tr>
<tr>
<td>Tip 900nm below the gate</td>
<td>1.51x10^{-4}</td>
</tr>
<tr>
<td>Tip in-plane with gate</td>
<td>2.71x10^{-5}</td>
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Table 1. Summary of \( \beta_F \), \( \beta_G \), and the ratio of \( \beta_F / \beta_G \) from 3-terminal and 4-terminal data.
different pressures from 5x10^{-6} to 1x10^{-3} Torr. As shown in Figure 15, the linear relationship holds between pressure and the ratio of the ion current to the electron current. Both Correlation Coefficient (R) values of these two devices are very close to +1 indicating that the pressure and the ratio of the ion current to electron current are highly correlated. The Standard Deviation (SD) shows that all the data gathered tightly. From the linear relationship between pressure and the ratio of ion current and electron current, the ionization cross section can be estimated. Using equation (5), and knowing electron current, pressure, and L, the ionization cross section is estimated to be (1.2x10^{-16} cm^2), which is fairly closed to the value (1.5x10^{-16} cm^2) we obtained from the literature [8].

VI. DISCUSSION

The turn on voltage of the double gated VA-CNF field emitter array presented in this paper is comparable to values reported by Dvorson et al [6,12,19] and Chen et al [14]. This is consistent with the values of the gate and focus field factors extracted from the data and the tip radii obtained from SEM metrology. The CNFs are expected to have a tip radius distribution [10l], resulting in a distribution of the field factors [20] which implies that the turn on of the device will be dominated by the smallest tip radii. This in part explains why the tip radii extracted from the IV characteristics and Fowler Nordheim analysis seems to be much smaller than radii been obtained from the SEM or projected from the analysis of catalyst size.

Our four terminal IV characterization of the double gate VA-CNF field emitter array suggest that the ratio of the focus field factor to the gate field factor (F/G) is an excellent indicator of the relative position of the carbon nanofiber relative to the extraction gate and the focus gate. From the fits of the experimental data, the extracted values of focus (F) and gate (G) field factors clearly show that when the CNF tip is in the same plane as the extraction gate electrode, the ratio of the focus field
factor to the gate field factor (F/G) is 0.26. This is consistent with geometric arguments that both the gate and the focus have a direct line of sight view of the emitter tip with the gate being closer and hence having a higher field factor. However, the gate field factor is not significantly higher and F/G would be of the order 0.1 – 0.5. Using exact geometric dimensions of the double gated VA-CNF field emitter structure, simulations show that F/G is 0.26. On the other hand when the tip is below the gate and there is no longer a direct line of sight view of the tip from the focus; (meaning that the tip is screened by the gate), using the same geometric arguments, one would expect the ratio of the field factors to be much smaller than 0.1. Simulations using the exact geometric dimensions show that F/G is 0.02 which is consistent with the fact that the focus is screened by the gate. The value of F/G extracted from the experimental data is 0.02 which is consistent with both the geometric arguments and the simulations. Neo et al recently reported double gated FEAs which use a volcano structure in which the focus electrode is placed ≈ 500 nm below the tip and the extraction gate completely shielded the tip from the influence of the focus electrode [21]. While they did not specifically calculate F and G, the focus transfer characteristics of their device showed that the emission & anode currents are only weakly dependent on focus voltage. Their results suggested that F is very small and F/G is also very small i.e. <0.01. The values of F/G and the dependence on the position of the tip relative to the planes of the gate and focus electrodes are consistent with earlier work by Dvorson et al [6,12,19], Chen et al [14], Itoh et al [22], Yamaoka et al [23] and Hosono et al [24]. Neo et al further examined double gated volcano field emitter arrays and their focusing properties in more detail [25]. From the focus transfer characteristics of these devices, the focus practically has no effect on the anode current or the emission current when the focus is fully shielded by the gate from the influence of the focus. In the other structures there was a greater dependence of anode and emission current on the focus voltage. This is confirmed by the total emission current obtained from the three structures when the focus voltage VF is 60 V and 5V.

The linear dependence of the ratio of the ion current to the electron current (II/IE) when the double gated VA-CNF field emitter array is used as an electron source for the impact ionizer suggest that there is a single dominant impact ionization cross section and that the gas molecules are singly ionized. For the study of the pressure dependence of the ionizer, the focus and gate voltages were both kept at 250 V while the anode/screen was biased at 400 V. Thus the energy of the electron is slightly outside the region of maximum impact ionization cross-section [8]. Bower et al demonstrated an electron impact ionizer based on CNT field emission electron source [26]. Their device is based on a CNT forest as the emitter and a suspended and perforated MEMS structure as grid. The device was generally operated at higher pressures than the current device, the ion current are generally comparable for Ar. At a pressure of 1 mTorr the current device demonstrated an ion current to emission current ratio 10-2 while the device reported by Bower et al demonstrated a corresponding ion current to emission current ratio of 10-4. The difference in current ratio could perhaps be explained by their device structure which is not self aligned leading to excess grid interception. In later work by Natarajan, the device performance improved by an order of magnitude by using a four electrode structure. The improved performance was attributed to an increase in the electron current contributing to ionization and improved ion collection efficiency [27]. At a pressure 1 mTorr the ion current to emission current ratio improved to 10-3. These results are in general agreement with recent work on Bayard-Alpert vacuum gauges based of field emitted electron sources [28, 29, 30, 31]. The vacuum gauges determine pressure by measuring current resulting from electron impact ionization. The ionization gauges are able to obtain higher ion currents per field emitted current by increasing the ionization path length and ion collection efficiency though the device construction.

VII. CONCLUSION

Double-gated field emitter arrays with isolated vertically aligned carbon nanofiber tips were fabricated using a photoresist planarization technique. Two types of devices were fabricated. The first device has the emitter tip in the same plane as the extraction gate and second device with the emitter tip 900nm below the extraction gate. All devices were made using a process which results in gate and focus diameters of 1.7µm and 4.2µm, respectively. Devices were first characterized as field emitters. From the three-terminal IV characteristics, the tip radii were extracted using the MATLAB models. The four-terminal IV characteristics yielded gate and focus transfer characteristics of the double-gated VA-CNF field emitter arrays. The devices showed different characteristics due to the relative positions of the tip with respect to the extraction gate. Total emission currents for both devices were computed and applied in the generalized FN equation to extract the values of gate and focus field factors. Electron impact ionization characterization of Ar was conducted using the double gated VA-CNF as the electron source. The results show that the ion current varies linearily with electron current at a fixed pressure and that there is a linear relationship between the ratio of the ion current and the electron current and pressure as expected from theory.

ACKNOWLEDGMENT

The authors would like to thank the help of the staff of Microsystems Technology Laboratories and the staff of NanoStructures Laboratory at MIT during device fabrication. The VA-CNFs were grown at the Cambridge University Engineering Department fabrication facility.
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[18] Origin Pro7 software package obtained from OriginLab www-originlab.com

