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A miniature electron ionization source fabricated using microelectromechanical systems (MEMS) with integrated carbon nanotube (CNT) field emission cathodes and low-temperature co-fired ceramics (LTCC)

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ABSTRACT

The use of microelectromechanical systems (MEMS) components in miniature mass spectrometers is particularly attractive due to their small size and scalable manufacturing capability. Our group has pioneered the development of miniature electron ionization sources combining MEMS fabricated structures with integrated carbon nanotube (CNT) cold-cathode field emitters. However, until now they have been of limited use due to the limited ability to direct the ions into a mass analyzer. In this work, we design a miniature ion source using a microfabricated MEMS device and a low temperature co-fired ceramic (LTCC) carrier that includes electrical connections, ion optics for directing ions out of the device, and a sample inlet. We present the design and fabrication of the ion source; simulate the energy and angular dispersion; and experimentally determine the energy and angular dispersion.

1. Introduction

Miniature mass spectrometers have a plethora of potential applications in environmental monitoring [1], security and defense [2,3], point of care medicine [4], and space exploration [5]. The use of microelectromechanical systems (MEMS) for components in miniature mass spectrometers is particularly attractive due to their small size and scalable manufacturing capability [6,7]. MEMS components have been investigated for multiple subcomponents including ion sources [8–13], inlet systems [14,15], mass analyzers [16–21], detectors [22–26], and vacuum components [27–30]. The MEMS fabrication process combines μm-scale lithography and thin-film deposition methods to consistently outperform conventional machining of small-scale geometries. Multilayer low temperature co-fired ceramic (LTCC) materials have many applications in packaging of microelectronic components [31]. LTCC is particularly useful in packaging of MEMS devices due to its hermeticity, similar thermal expansion coefficient to silicon, and the ability to make cavities in the multilayer structure [32,33]. In addition to MEMS packaging, LTCC utilization continues to expand into other fields of research including LTCC-based compact, light-weight, high-speed antennas for portable electronic devices; [34] advanced packaging options for chemical sensors to improve design, integration, and advanced functionality; [35,36] hybrid integration of LTCC with Si for packaging systems with integrated electrical interconnects; [37] and a reliable multilayer substrate material for silicon based MEMS component packaging [32]. LTCC materials have also been used to develop miniature mass spectrometer components such as ion traps [38].

Carbon nanotubes (CNTs) have attracted much attention as a high-performance reliable field emission electron source [39–41]. They offer several benefits over traditional filament thermionic emitters in terms of power, lifetime, and current density [42]. Sev-

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eral groups have demonstrated miniature ion sources using field emission cathodes. Velasquez-Garcia, et al., demonstrated a MEMS based electron ionization (EI) gas ionizer with an integrated extractor gate with uniform emission current and up to 19% ionization efficiency [9]. Chen, et al., reported a micro-fabricated double-gated carbon nanofiber MEMS EI and field ionization device with an order of magnitude lower power requirements and turn-on voltage when compared to a thermionic emission EI source and a tungsten ionizer respectively [12]. Tassetti, et al., reported a MEMS EI source integrated in a micro time-of-flight spectrometer with the ion source and the analyzer fabricated on the same substrate [10]. Our group has pioneered the development of a MEMS vacuum microelectronic device platform with integrated CNT cold-cathode field emitters for a variety of applications [16,43–50]. Using the vacuum microelectronics platform, EI sources have been produced and used to generate ions with trajectories parallel to the MEMS substrate for various analytes over a wide pressure range [43,45]. However, these EI sources have been of limited use for mass spectrometry applications as the ion trajectories are parallel to the substrate which limits their ability to direct the ions to a separate mass analyzer.

In this paper, we describe the development an electron ionization source using a Neir type geometry [51] by combining a MEMS device with integrated field emission cathode with a LTCC scaffold that facilitates directing ions to a separate mass analyzer. We report on the ion source design and fabrication, the results of a SIMION simulation, and provide experimental measurements of the ion source energy and angular dispersion.

2. Ion source design and fabrication

A traditional Nier-type ion source ionizes gas molecules using an electron beam traveling perpendicular to the path the ions will travel. The source is composed of an electron beam inlet, anode, extraction aperture, and repeller arranged in a rectangular box structure (Fig. 1a). An external magnetic field aligned with the desired electron beam path is often used to help confine the electron beam and increase the path length of the electron trajectories [51]. The potential on each electrode, and geometry of the electrodes are chosen to direct ions through the extraction aperture towards the spatial filter with minimal energy and angular dispersion. After the extraction aperture, several additional apertures can be added to collimate the ion beam. Finally, a spatial filter is placed at the exit of the ion source and entrance of the mass analyzer, and the sample inlet is a small hole in the ionization volume. Typically, the ionization volume is constructed using metal plates for the electrodes separated by insulating spacers. The electrical connections are made by attaching wires to the various electrodes. To achieve this in a miniature form factor, we fabricate a MEMS device using our vacuum microelectronics platform that includes carbon nanotube field emission cathodes and an ionization volume. We place the MEMS device in a LTCC scaffold to enclose and electrically connect the MEMS device and provide support for an extraction aperture and spatial filter. In this miniature format, the magnetic field does not cause a significant increase in ion path length typical of macroscopic Nier sources due to the small ionization volume, however, the confinement of the electron beam to limit its angular dispersion is similar to macroscopic sources. The following sections provide details on the design and fabrication.

2.1. MEMS device design and fabrication

Prior publications describe our MEMS vacuum microelectronics platform and present specific details related to general design and fabrication [43]. Briefly, the Polysilicon Multi-User MEMS Process (PolyMUMPs [52]) three-layer polysilicon surface micromachining process is utilized. Sequential deposition of polysilicon and sacrificial oxide layers, along with standard lithographic patterning and etching, allow for fabrication of the electrodes and support structures (Fig. 2a). Polysilicon device structures are released from the substrate by removal of the sacrificial oxide using an HF etch

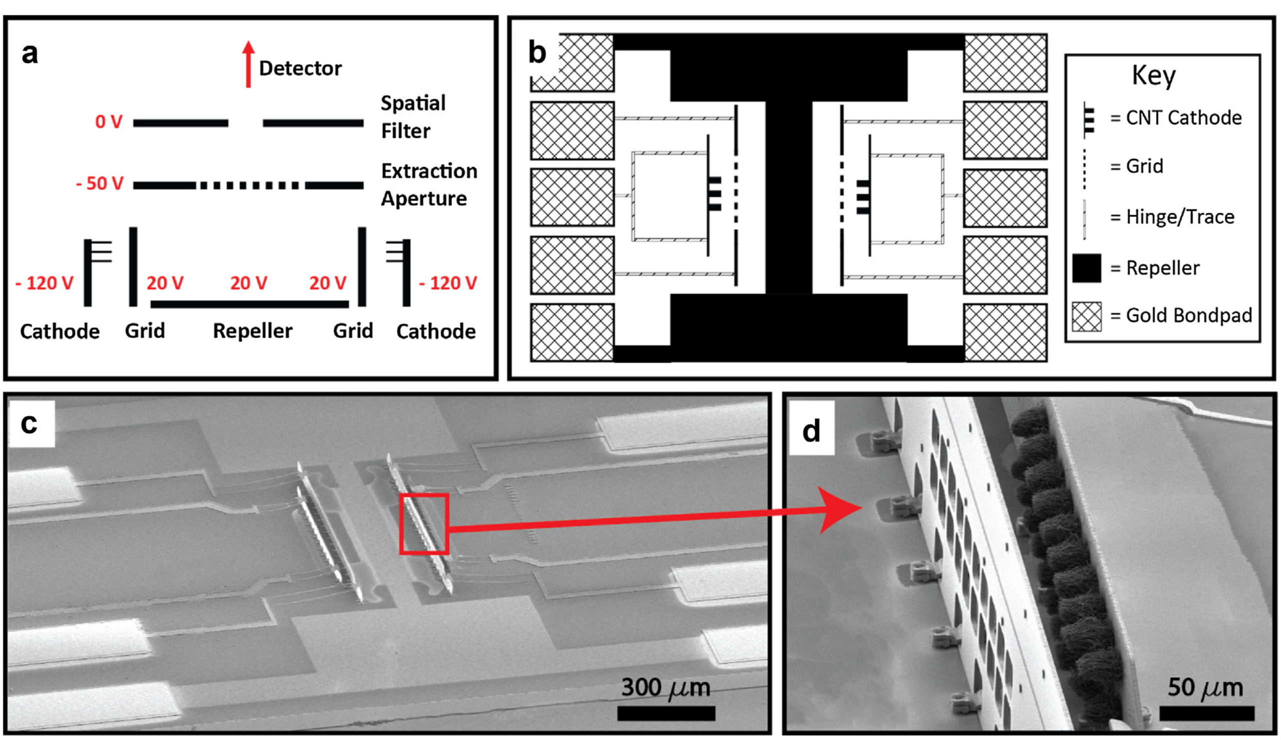

Fig. 1. (a) Cross section schematic of ion source, including LTCC electrodes, with experimental potentials labeled; (b) top-down schematic of MEMS device with symmetric cathode and grids; (c) scanning electron micrograph (SEM) of fully assembled MEMS device; (d) SEM of CNT field emitters which are synthesized at specific locations to align with the grid and at specific lengths directly on cathode prior to assembly.