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Integrated Carbon Nanotube Field-Emission Electron Sources: An Enabling Technology for Vacuum Microelectronics and Miniaturized Sensor Development

The use of cold cathode field electron emitters in new age vacuum microelectronic devices (VMDs) brings together the best features of the long-standing vacuum tube (e.g., high power) with the proven benefits of solid state power transistors (e.g., long lifetime and miniaturization). Cold cathode devices have the advantage of instantaneous turn-on, low energy consumption, and microscale integration capabilities. Recently, nanomaterials have exhibited themselves as promising candidates for cold cathode electron emitters. In particular, carbon nanotubes (CNTs) feature many excellent FE qualities such as extremely high aspect ratios, excellent electrical and mechanical properties, high thermal and electrical conductivity, and high chemical stability. In this presentation, novel VMDs that employ CNT field emitters, and their enabling constituents, pertaining to the unique materials growth and device design, will be discussed.

The first study investigates the development of a novel chemical ionization (CI) electron/ion source to be utilized in portable commercial explosive trace detection mass spectrometers. Chemical ionization mass spectrometry (CI-MS) is advantageous for the selective identification of explosives as they can be negatively ionized more easily than most interferents because of the strong electron affinity of the nitro group of these compounds. However, gas requirements, power consumption, and inadequate lifetime are often limiting factors for the use of conventional ion sources in portable mass spectrometers. In order to correct for these limitations, a direct fit and replaceable CNT field emission based source was designed to be viable in the conditions present during CI-MS. Our research focused on catalyst and substrate engineering for CNT emitter adhesion, CNT growth, electrode placement and parameters to optimize transmission, and evaluation of device performance against standard filament thermionic electron emission sources in a commercial mass spectrometer. We demonstrated excellent operating voltages and an average lifetime of 320 h when operated in constant emission mode under elevated CI pressures. Furthermore, cycling abilities add to device lifetime and reduced power consumption without sacrificing performance and detection capabilities. Collected spectra analysis revealed very similar *m/z* peaks in operating modes when compared to the filaments.

In an ongoing and more recent study, we've focused on the integration of the as-grown CNT emitters with microscale platforms, specifically microelectromechanical system (MEMS). This work focuses on a monolithic vacuum microelectronic integration platform that allows for on-chip integration of CNT-based cold cathodes with electron/ion optics. VMDs designed for practical circuit implementation, such as vacuum microtriodes, tetrodes, and pentodes, to enable high performance amplifiers, oscillators, and logic circuit design were explored. Furthermore, these VMD's can be designed to provide on-chip analyte ionization and extraction for use as a micron ion source for miniature sensor development (e.g., miniature mass spectrometers). Combining this versatile platform with advanced multi-layer packaging technology, such as low temperature co-fired ceramic (LTCC) structures, allows us to develop miniaturized sensors capable of advanced detection.