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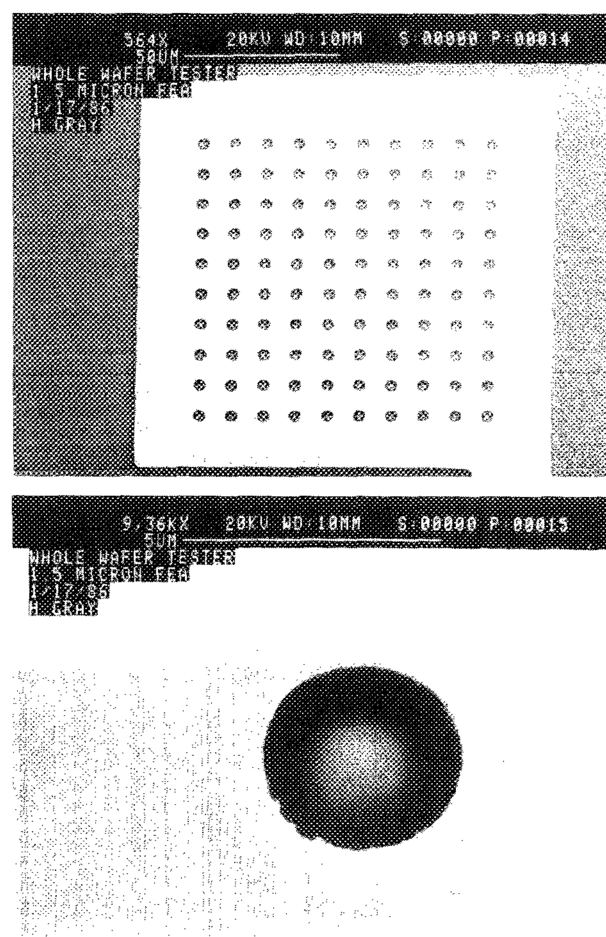
The device reported here allows the researcher the opportunity of gaining primitive yield information, threshold voltages, emission stability, and other information, e.g., gas effects, on field emitter arrays (FEA) which are microminiature "vacuum tubes" fabricated by microelectronic processing methods on silicon wafers, without scribing, dicing, and mounting each device on individual vacuum-compatible headers. This device also speeds up the entire data-acquisition process by requiring only one ultrahigh-vacuum pumpdown and one set of vacuum feedthroughs.

INTRODUCTION

Field emitter arrays (FEAs) are devices consisting of a number of micron-size integrated field emitters which are fabricated simultaneously on a single substrate. These devices promise high electron current density, low operating power, wide temperature range operation, and narrow energy spread. For example, at least one of these technologies has reported current densities greater than 320 A/cm^2 in essentially a dc mode[1]. At least four different basic fabrication technologies have been reported.[2–5] The device shown in Fig. 1(a), fabricated at the Naval Research Laboratory (NRL),[4] was fabricated on a 2-in. silicon wafer using standard silicon microelectronics processing methods. Figure 1(b) shows that each field emitter cell in the array has an extraction aperture whose diameter is about 1–4 μm, centered on its field emitter both vertically and horizontally in the extraction grid plane. This close spacing between the field emitter and the extraction grid allows extraction voltages of less than 200 V compared to classical electron field emission voltages of 3–10 kV. Because each cell is a miniature field emitter "gun" with small grid-to-emitter spacing, field emitter array cells can be packed together tightly without the emission characteristics of one cell affecting its neighbors. To date the neighbor–neighbor distance is 5–10 μm.[4] FEAs typically consist of a set of 1–10 000 cells in a single emitting device, depending on the intended use of the device. Devices fabricated at NRL usually consist of 10×10 cells in a square array. As shown in Fig. 2, each FEA device is centered in a 1-mm field which includes a bonding pad for electrically connecting it to the pins of a TO-5 header for emission testing and other experiments. The testing of each FEA device requires that the silicon wafer be scribed and diced into pieces consisting of one or more devices; then each piece must be bonded to the header and wirebonded. The probability of damaging these 3-D submicron structures during the mechanical assembly operations is quite high. In addition, such fabrication steps are expensive and time consuming. Furthermore, once the wafer has been diced into pieces, additional processing of the devices on that wafer is impossible.

The wafer tester reported here allows field emitter arrays to be tested and characterized in ultrahigh vacuum by using the entire FEA wafer, or a major part of a wafer. Once having been tested in the FEA wafer tester, these wafers can be returned to the processing sequence for further fabrication or device modification, or the devices can be analyzed separately by scanning electron microscopy (SEM), second-



(a)

(b)

FIG. 1. (a) A scanning electron micrograph of a 10×10 silicon field emitter array (FEA) fabricated at the Naval Research Laboratory (NRL). The field emitters are single-crystal silicon pyramids integral with the (100) substrate. (b) A scanning electron micrograph of one representative field emitter cell from the 10×10 array. Note that the field emitter is centered both vertically and horizontally in the extraction electrode aperture.

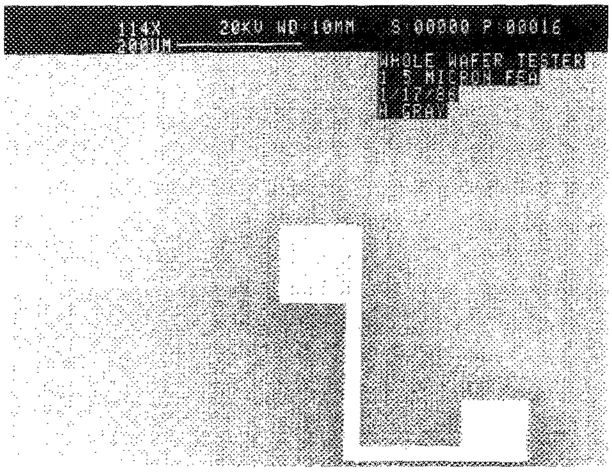


FIG. 2. An optical micrograph of the NRL 10×10 silicon FEA inside its 1×1-mm field. Note the gold bonding pad at the lower right-hand corner and the 1.5-μm design marker in the upper left-hand corner.

ary ion mass spectroscopy (SIMS), or Auger electron microscopy (AES).

I. HARDWARE

Because chemisorption and physisorption of contaminants, particularly hydrocarbon species, are known to adversely affect electron emission from sharp field emitters by raising the tip's work function, or in some cases by actually building up deposits so that the tip's radius of curvature is increased, an oil-free, ultrahigh-vacuum system is required to prevent back-ion bombardment and subsequent changes in the work function or morphology of the emitter tip. In order to satisfy the above criteria, a Perkin–Elmer model TNB-X UHV surface-science vacuum chamber,[6] which is pumped by a titanium/tantalum 200-1/s ion pump, was chosen for the vacuum system.

As shown schematically in Fig. 3, the wafer tester chamber consisted of a 4-in.-i.d stainless-steel nipple modified to include a port to hold a movable probe assembly, and a zero length window for observation of the FEA wafer through a long focal length optical microscope. In order to maximize pumping throughout and to minimize the ambient gas environment, this wafer tester chamber was bolted onto the 4-in.-i.d. port of the surface-science vacuum system which is normally reserved for a specimen manipulator.

Since the silicon wafer is an integral part of the silicon field emitter array, and since the wafer sits directly on top of a stainless-steel platform, the platform was insulated electrically from the chamber by 0.25-in.-thick Teflon sheets. The electrical connection to this platform was made through a side port in the surface-science chamber (not visible in Fig. 3). The collector and grid potentials were brought in through a port on the UHV X–Y–Z manipulator[7] which was attached to one of the side ports of the experimental chamber. This movable collector-grid assembly was constructed using the following criteria: (1) The grid voltage could be applied to any particular FEA cell bonding pad (100×100 μm) by moving the X–Y–Z manipulator. (2) The FEA device and bonding pad, as well as the voltage

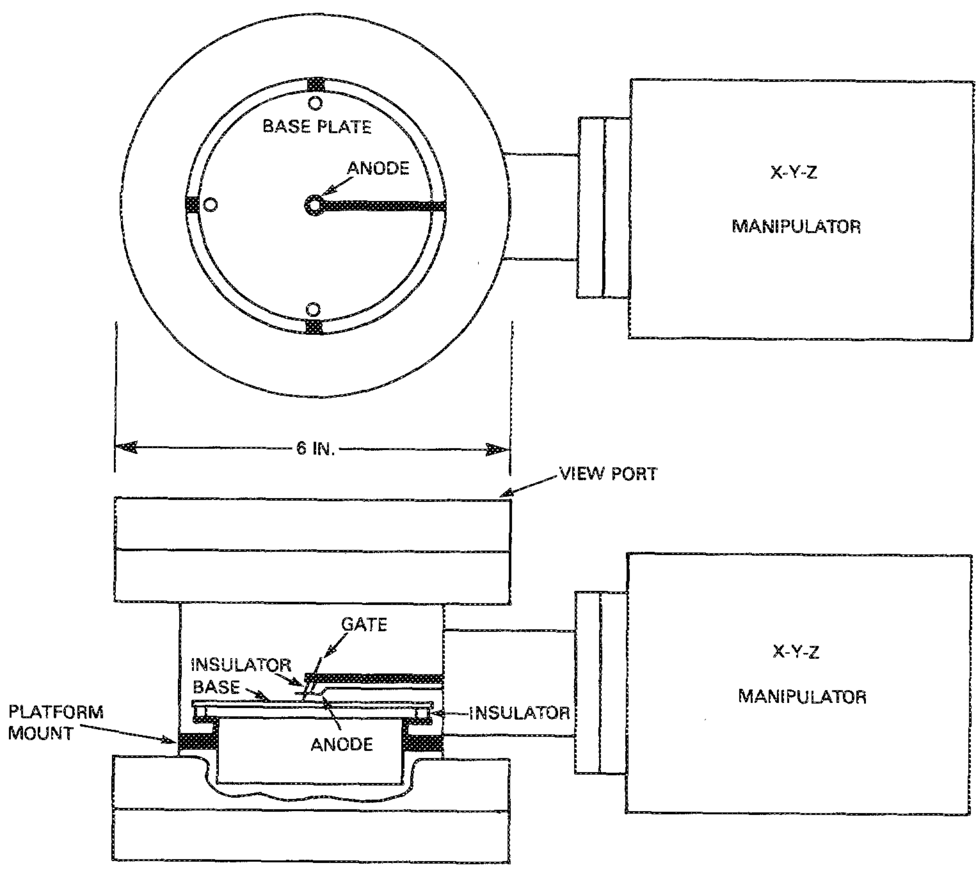


FIG. 3. Schematic diagram of the whole wafer FEA tester. All vacuum components are UHV compatible, namely 304 stainless steel, alumina ceramics, and Teflon.

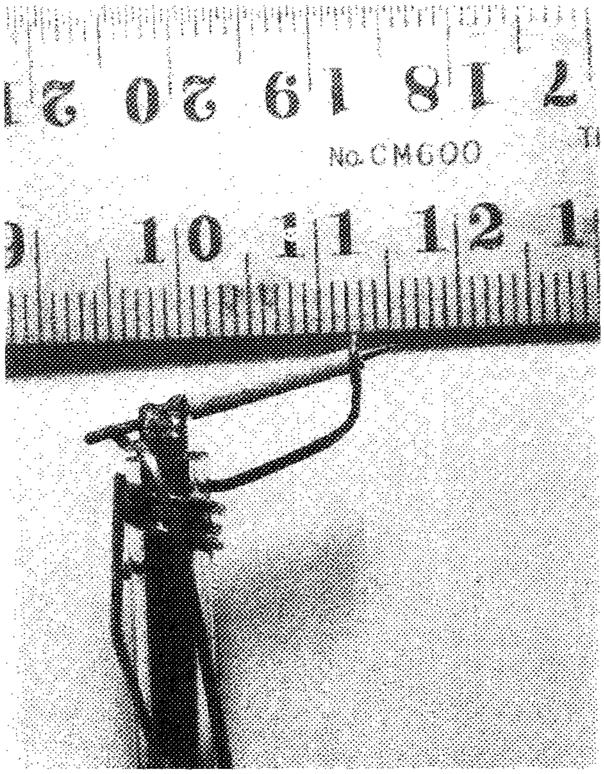


FIG. 4. A photograph of the grid-collector assembly. Note the ring collector surrounding the grid needle.

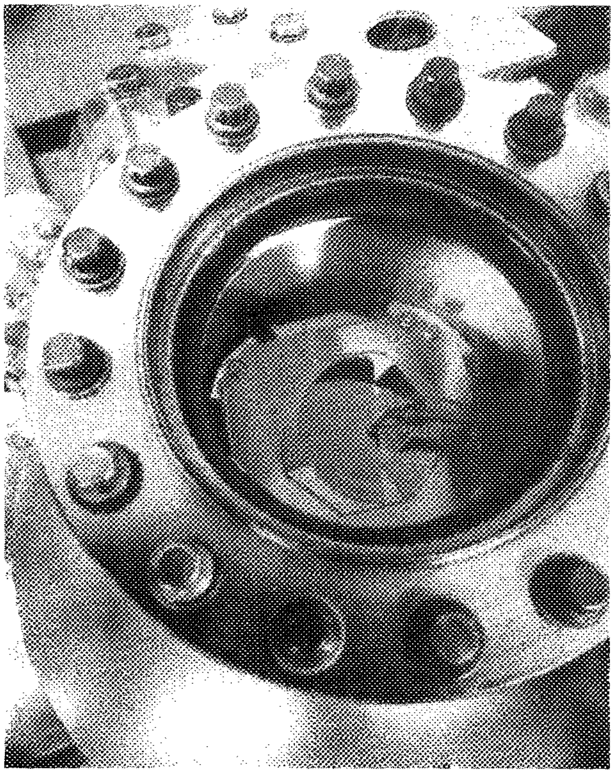


FIG. 6. A photographic view through the 6-in.-o.d. viewport of a half-wafer FEA under test. Note the grid-collector probe entering the chamber from the right side as well as the small FEA device sizes seen in the wafer fragments surrounding the half-wafer under test.

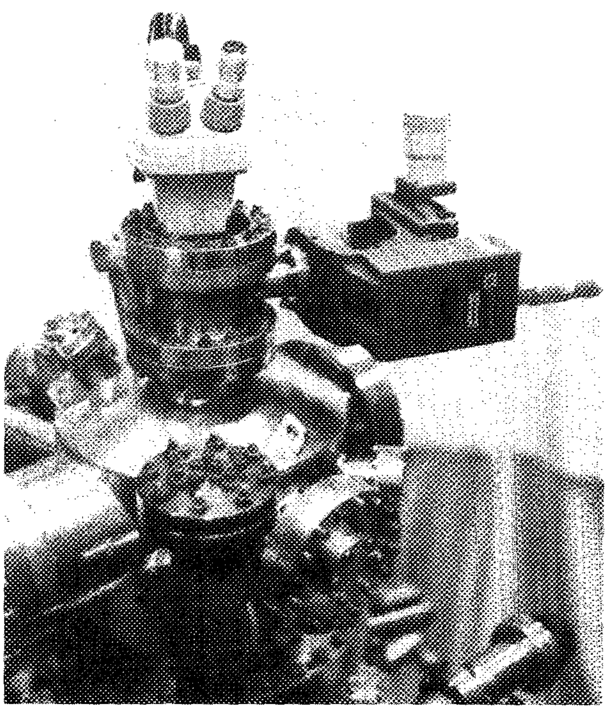


FIG. 5. A photograph of the completed whole wafer FEA tester attached to the surface-science pumping system.

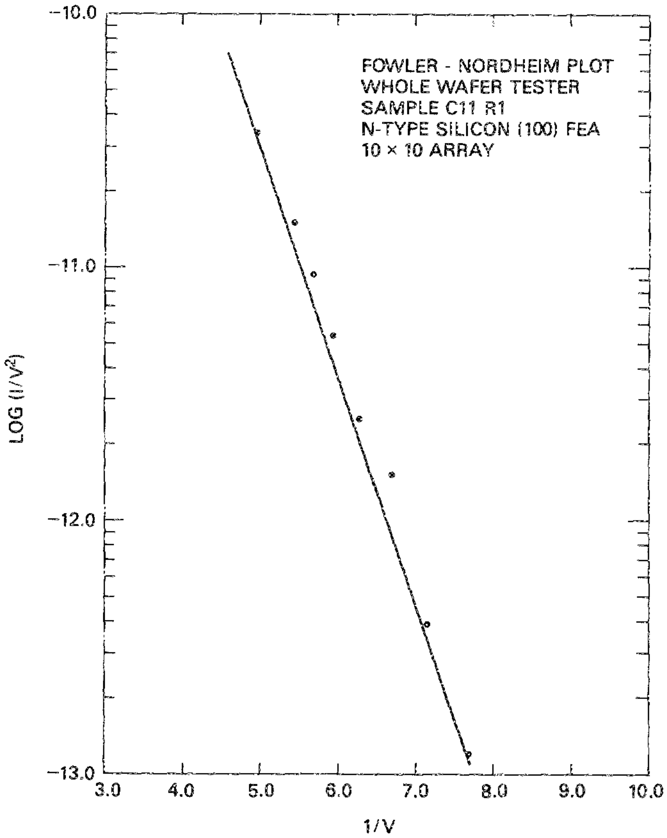


FIG. 7. A Fowler–Nordheim plot of electron field emission obtained from FEA device C11R1 on the half-wafer shown in Fig. 6. Note that the data follows the classical Fowler–Nordheim straight line within the measured voltage range.

TABLE I. Raw current/voltage and reduced data for a Fowler–Nordheim plot of electron field emission from silicon FEAs.

Base current I_b (10^{-6} A)	Collector current I_c (10^{-6} A)	Corrected voltage V (V)	$1/V$ (10^{-3} V^{-1})	$1/V^2$ (10^{-11} V^{-2})	$\mathrm{Log}(I_c/V^2)$
1.4	1.4	204	4.91	3.4	−10.47
0.52	0.52	184	5.44	1.5	−10.81
0.29	0.29	177	5.66	0.93	−11.03
0.15	0.15	168	5.94	0.53	−11.28
0.064	0.064	159	6.28	0.25	−11.60
0.035	0.035	150	6.68	0.16	−11.81
0.0075	0.0075	140	7.15	0.038	−12.42
0.0020	0.0020	130	7.69	0.012	−12.93

probe needle, could be observed through the 6-in.-o.d. zero length window using a long focal length lens. (3) The electron collector would be small enough so that (1) and (2) could be easily accomplished. The collector was designed as a simple wire which was fabricated into a ring electrode around the grid voltage probe and insulated from it. The collector, therefore, moves with the grid voltage probe and resides approximately 2 mm above the FEA device when data is being taken. The probe assembly is shown in Fig. 4. Figure 5 is a photograph of the completed wafer tester assembly attached to the surface-science chamber. Figure 6 is a photograph of a half-wafer FEA in the process of being probed for electron field emission.

The wafer tester consists of standard UHV materials, and it can be baked at 100–120 °C for several hours to achieve pressures in the 10^{-10}–10^{-9}-Torr range.

II. PERFORMANCE

Typically, voltages from 0–250 V are applied to the extraction grid of these silicon 10×10 FEA device structures. The collector is usually biased at 400–600 V. Measured leakage currents through the SiO_2 insulating layer, as well as through the collector electrode insulators, are typically less than 10^{-10} A.

Figure 7 is a Fowler–Nordheim plot of field emission obtained from one 10×10 silicon FEA device on a half-wafer. Table I contains the raw current/voltage and the reduced Fowler–Nordheim data used in Fig. 7. The data was reduced by decreasing the applied voltage by the IR drop (i.e., current $\times$ resistance) across protection resistors in both the base and extraction electrode legs. Using Table I, note that almost no emitted current is intercepted by the extraction grid or by the grid voltage probe needle assembly. It is this lack of current interception by the probe needle which makes the FEA wafer tester most valuable.

After the FEA devices have been characterized using the FEA wafer tester, the wafer can then be processed further, or it can be scribed, diced, and individual devices can be mounted on TO − 5 (or similar) headers/packages to be used as electron sources for experiments or fundamental measurements.

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