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Battery-operated atomic force microscope

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The design of a battery-operated atomic force microscope (AFM) using a piezoresistive cantilever is described. The AFM is designed so that all power to drive the scanning tube and detection electronics comes from a self-contained battery. The prototype AFM uses a 6 V, Ni–Cd, camcorder battery, however, any battery that supplies between 6 and 12 V may be used. Scanner control and data acquisition are implemented using commercially available software running on an external computer. The prototype AFM achieves a scan area of 53 by 53 μm, consumes 1.8 W of power, and can scan continuously for about 7 h on a single battery charge. © *1998 American Institute of Physics.* [S0034-6748(98)05501-4]

I. INTRODUCTION

Scanning probe microscopes (SPMs) in general, and atomic force microscopes (AFMs) in particular, have had dramatic impact on the ability to measure surface properties at nanoscales in a wide variety of applications.[1–3] Most implementations of AFMs, including all commercially available units, are relatively large and ultimately rely on electric power coming from a standard main supply (110 V, 60 Hz, for example). High voltage, typically on the order of ±200 V, is required to drive the scanning stage of the AFM, which uses piezoelectric actuators. Also, +15 and −15 V supplies are required to power the control electronics, which generate the scan signals and detect the cantilever deflection. In addition, the data acquisition and image processing systems usually run on a computer. The total power consumption for AFM systems typically range from about 600 to 1800 W, and they weigh on the order of 10–100 kg.[4,5]

The weight and utilities requirements to run an AFM preclude its use in remote locations, such as in space, or for *in situ* geological and biological studies. In this article, we demonstrate a battery operated, lightweight AFM, with a scan range of 50×50 μm. The AFM uses a dc-to-dc converter to step up the battery voltage to about +215 V to drive the piezoelectric scanner. We designed a novel, low-power consumption, high-voltage amplifier to allow 7 h of uninterrupted operation from a 6 V, 2.4 A h, Ni–Cd battery. Our demonstration system still requires utility power for the data acquisition computer and controller, however, a battery powered laptop computer with the proper interface could be used instead. Our work holds promise for further development and miniaturization of autonomous SPM measurement devices and related instruments.

II. DESCRIPTION OF THE MICROSCOPE

The design of the battery-operated AFM (referred hereafter as BAFM), including the electronic circuitry, control and data acquisition approach, and physical construction are presented and discussed in this section. The simplicity and modularity of the AFM are emphasized.

Figure 1 schematically depicts the first prototype of the BAFM. The footprint of the entire microscope is about 102 ×269 mm. Its height from the base to the top of the z adjustment screw is about 250 mm. Its mass is approximately 6.8 kg. The sample rests on a platform supported by a ball bearing x-y stage. Micrometers on the adjustment screws allow the sample to be positioned to within about ±5 μm over the travel range of 10 mm in x and y. The x-y stage is in turn mounted on a leveling stage that allows the sample platform to be oriented with respect to the vertical axis of the piezoscanner.

The BAFM uses a piezotube scanner, 63.5 mm long, made of PZT-5H. The piezotube is mounted in a cylindrical housing assembly that slips into a cylindrical mount, which is, in turn, fastened to the z-positioning stage. The housing assembly is located by spring-loaded ball detents and a shoulder in the cylindrical mount. The scanner module was designed so it could be easily removed and allow the cantilever to be readily changed.

The cantilever mounts on a small block of PVC plastic glued to the protruding end of the piezotube. The mounting block has two spring clips which hold and make electrical contact with the piezoresistive cantilever. Wires to the cantilever and piezotube are routed inside the tube up to connectors at the top and side of the module.

The piezotube mount is attached to a crossed roller bearing slide assembly. The slide is positioned vertically by a 1/4–80 fine pitched screw that has a small and large diameter thumbwheel attached at one end. The thumbwheel enables coarse and fine positioning of the scanner assembly. The z stage also incorporates a machined brass gib and clamp screw, so that the stage can be firmly held during scanning or transport.

The z stage is attached to a rectangular housing made of aluminum plates. The housing provides a relatively rigid means to support the scanner and additionally serves as an enclosure for the microscope's electronics. The electronics are mounted in a rack module that slides into the housing. The handle at the top of the unit has the dual purpose of being a carrying handle for the entire microscope as well as the electronics module itself. The electronics module can be

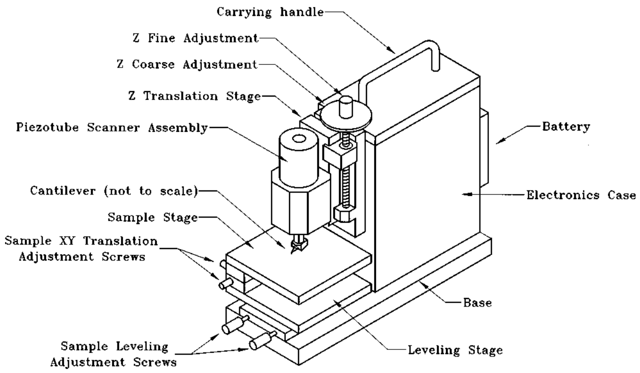

FIG. 1. Pictorial diagram of the prototype battery-operated atomic force microscope (BAFM).

accessed by removing screws at the top and sliding it out by pulling on the handle.

Circuit boards slide into horizontal slots machined in the rack sidewalls, with the back wall serving as a stop. The rack is self-contained, so there are no hard-wired connections between it and the battery. Power connection to the electronics module is made by a brass leaf spring attached to the battery mount on the rear of the rectangular structure and a brass pin mounted on the module. Electrical connection of the battery to the electronics rack occurs when the rack is inserted into the rectangular housing.

The battery which powers the BAFM, mounts at the rear of the electronics housing (not shown). The prototype uses a battery from a video camcorder to make the power supply practical and low cost. The mount is virtually identical to those found on camcorders.

A. Electronics and control

Figure 2 shows an overall schematic diagram of the electronics associated with the BAFM. The major subsystems are: the battery, the dual low-voltage dc-dc converter, the high-voltage dc-dc converter, the tube deflection amplifier, the cantilever deflection amplifier, the computer, and the waveform rectifier. The low-voltage dc-dc converter produces nominally ±12 V, which powers the op-amps and other active components used in the tube deflection and tip deflection amplifier subsystems. The high-voltage converter, used to drive the piezotube scanner, steps up the battery voltage of 5–12 V to approximately +215 V.

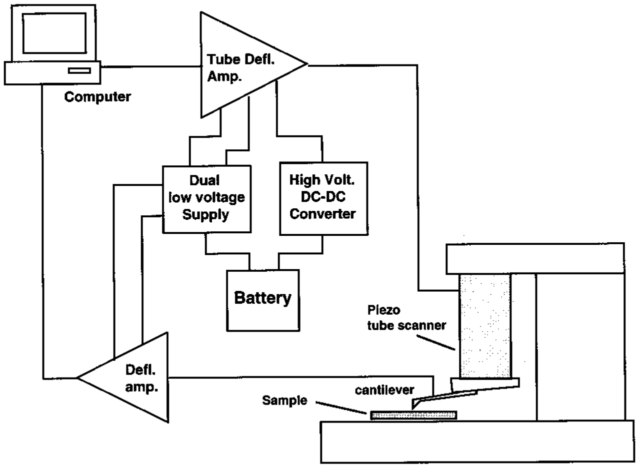

FIG. 2. Schematic diagram showing the layout of the battery-operated atomic force microscope. The prototype microscope, uses a 6 V camcorder battery.

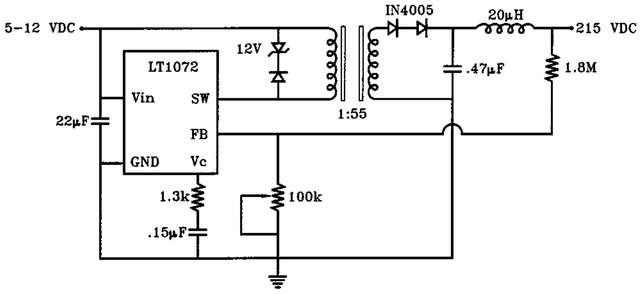

FIG. 3. Circuit schematic for the high-voltage dc-dc converter. This circuit steps up the battery voltage (4.8–12.2 V) to +215 V.

The first prototype of the BAFM uses a Panasonic, Ni–Cd, 6 V, 2400 mA h camcorder battery, however, any battery that supplies between 6 and 12 V will power the microscope. We chose to use a camcorder battery, because they are relatively inexpensive, readily available, and rechargeable.

Figure 3 shows a schematic diagram for the circuit that steps up the battery voltage in order to drive the piezotube scanner. The circuit outputs a constant 215 V for voltage inputs between 4.8 and 12.2 V. Output voltage is regulated to within 0.5 V peak to peak, with a maximum secondary load current of 1.3 mA. The converter uses a modified flyback configuration based on the LT 1072 switching regulator IC.[6] The IC functions as a combination of a pulse-width modulator (PWM) and switch. At the beginning of the duty cycle, the switch turns on and energizes the primary windings of the transformer. The switch turns off when the current going through the switch reaches a predetermined level. When the switch turns off, the energy stored in the magnetic field induces a stepped-up voltage in the secondary windings. The output voltage is controlled through an error amplifier internal to the IC that compares the output voltage with a reference voltage and sets the current level at which the switch turns off. The transformer has a 55-to-1 turns ratio (20 turns on the primary, 1100 on the secondary) wound on a split-bobbin ferrite core.

Most AFMs use bipolar high-voltage supplies to maximize the deflection and extension of the piezotube scanner. We did not attempt to design a bipolar supply for the first prototype, so as to minimize power consumption and simplify the electronics. We chose to design our own high-voltage converter, because we could not find a commercially available low-power dc-dc converter having more than about 15% efficiency and that could operate on a wide input voltage range. Our converter is about 25%–30% efficient, and will operate normally for input voltages between 5 and 12 V.

There are alternative approaches for voltage conversion, such as a generic boost topology,[7] but these would require more components, more stages, and result in decreased efficiency in comparison to a flyback design. An additional advantage of a flyback converter is that it provides electrical isolation between high and low voltages.

Figure 4 shows a circuit schematic for the power supply

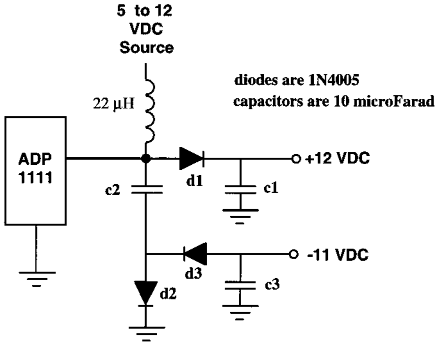

FIG. 4. Circuit schematic for the dual low-voltage power supply. The supply uses the ADP 1111 switchmode IC, boost stage and charge pump to generate approximately ±12 V dc for powering ICs in the microscope electronics.

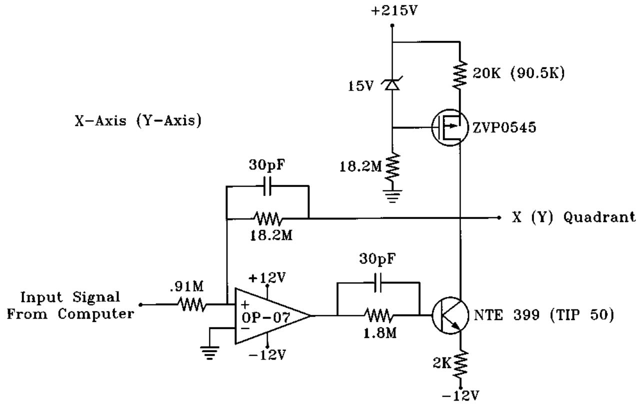

FIG. 5. Circuit schematic for piezotube deflection amplifier. One amplifier is used for each quadrant of the scanner tube.

used to power all the ICs (except the LT 1072). The heart of the circuit is the relatively new ADP 1111 switchmode IC.[8] The supply functions essentially as a boost regulator that also drives a charge pump to generate a negative voltage. A boost regulator takes a lower positive dc voltage and produces a higher dc voltage by means of a transistor switch that controls the charging of an inductor. Here, when the switch in the ADP 1111 is closed (essentially to ground), the inductor energizes. When the switch opens, current from the inductor charges capacitors $c1$ and $c2$. When the switch closes again, while the inductor charges, diode $d1$ keeps $c1$ from discharging, and the upper terminal of $c2$ is forced to ground potential. At this instant, the lower terminal of $c2$ carries a negative potential with respect to ground. This negative potential forward biases $d3$ and charges $c3$ (its upper terminal being negative with respect to ground). The average output voltage of the converter depends on both the load current and duty cycle of the switch.

We designed our own tube deflection amplifier, because most commercial high-voltage amplifiers consume more power, are usually not stable driving highly capacitive loads unless modified, and are physically larger than we desired. For example, commercial high-voltage operational amplifiers can draw quiescent current of 2 mA or more.[9] For an output voltage of 200 V, this corresponds to a power consumption of 0.4 W or more. In contrast, the power consumption of all four of our high-voltage amplifiers combined is about 0.5 W.

The schematic diagram for the piezotube deflection amplifier is shown in Fig. 5. Each of the four quadrants of the piezotube has its own amplifier. The differences between x-axis and y-axis amplifiers are the value of resistor in the current source and the type of NPN transistor, as indicated. The circuit uses a P-channel metal-oxide-semiconductor field effect transistor (MOSFET) as a current source and an ultralow offset voltage op-amp to amplify signals from the computer to control the voltage applied to the tube quadrants. The zener diode keeps the gate voltage of the MOSFET about 10 V lower than the source voltage. The 10 V drop across the 20 kΩ resistor (or 90.5 kΩ for the y-axis amplifier) essentially determines the quiescent current of the amplifier, about 510 μA for each of the x-axis amplifiers and 110 μA for each of the y-axis amplifiers. The op-amp controls the voltage at the output node by means of the NPN transistor. When the input signal from the computer is at 0 V, the transistor is turned on enough to conduct all the current from the current source to the -12 V supply. When the input signal from the computer is in its range of 0 to -10 V, the transistor turns off enough so that enough current is forced through the 18.2 MΩ resistor in the feedback path to keep the summation of currents at the noninverting terminal of the op-amp equal to zero. With the resistor values shown, the gain of the amplifier is set to about 20.

We constructed the amplifiers for the x and y quadrants differently to minimize power consumption. The piezotube scans more rapidly in the x direction than in the y direction to achieve a raster pattern, about 16 Hz in x compared to 0.03–0.25 in y. The quiescent current in the x-axis amplifiers is necessarily larger than that in the y-axis amplifiers, because of the higher scan rate in the x direction. Since the piezotube behaves like a capacitor (about 30 μF per quadrant), a larger current is needed in the x-axis amplifiers, because the tube velocity is proportional to the time rate of

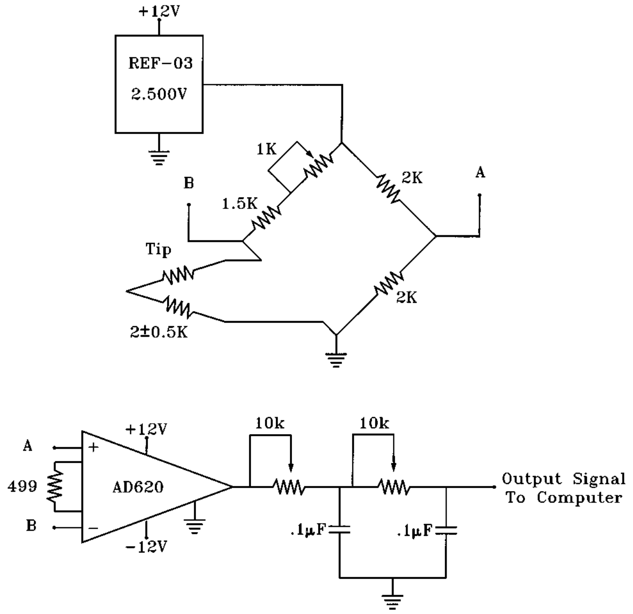

FIG. 6. Circuit schematic for the cantilever deflection amplifier circuit. The microscope uses a piezoresistive cantilever, which enables a very simple, low-power, Wheatstone bridge circuit to be used to detect the tip deflection.

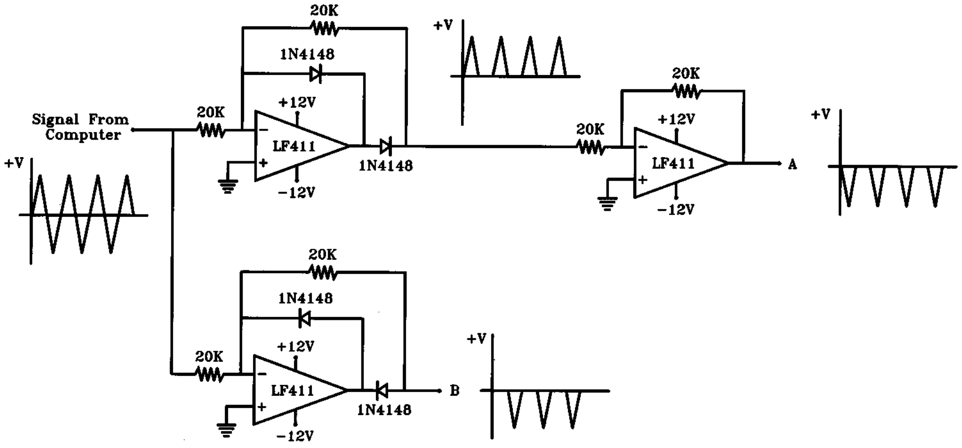

FIG. 7. Circuit schematic for input wave form rectifier. The circuit splits the full-triangle wave output from the D/A converter into a pair of synchronized half-triangle waves. The outputs from the rectifier are fed to the deflection amplifiers of opposing tube quadrants. This arrangement enables all four quadrants to be driven with only two D/A channels.

change of applied voltage, which is in turn proportional to the current charging the quadrant.

To simplify the detection of cantilever movement and minimize power consumption, we chose to use a piezoresistive cantilever. With this approach, the deflection of the cantilever is measured directly from its resistance change, so no external sensors are needed.[10] The detector is simply a Wheatstone bridge circuit in which the cantilever functions essentially as a variable resistor in one leg of the circuit. In SPMs that use a reflected laser beam to detect the deflection of the cantilever, the diode laser typically draws about 50 mA at 5 V, which results in about 250 mW of power consumed. In contrast, the piezoresistive cantilever bridge circuit presents a 2 kΩ load on 2.5 V, which results in about 3 mW of power consumed.

Figure 6 shows the circuit schematic for the deflection amplifier. The bridge is powered by a REF-3 precision 2.5 V reference, stable to within a few millivolts. All fixed resistors are metal film types, with tolerances better than 1%. The 2 kΩ resistors are matched within 1 Ω. A potentiometer used in conjunction with the 1.5 kΩ resistor, allows the bridge to be easily balanced out to 0 V whenever a cantilever is replaced. Two first-order low-pass filters were added to eliminate noise on the output. Total power consumption of the deflection amplifier circuit is estimated to be less than 75 mW. Gain bandwidth of the circuit is limited by the filters to approximately 3.6 kHz.

One limitation of our prototype is that we built only one high-voltage power supply, consequently, we have only one polarity available to apply to the tube quadrants. We compensated for this limitation by designing an externally-powered half-wave rectifier between the D/A output and each pair of tube deflection amplifiers. The rectifier takes the triangle wave output from the D/A converter and splits it into a pair of synchronized, negatively-going triangle waves. The outputs from the rectifier drive the high-voltage deflection amplifiers of opposing tube quadrants. This arrangement enables us to drive all four quadrants with only two D/A channels. Figure 7 shows the rectifier circuit schematic.

B. Control and data acquisition approach

Scanner control and data acquisition for the prototype BAFM were carried out using a personal computer, a plug-in data acquisition card, and LabView software.

We used a Pentium, 133 MHz personal computer with 32 MB of RAM running under Windows 3.11 for both data acquisition and control of scanning. We used a National Instruments AT-MIO-16X multifunction data acquisition card to interface with the BAFM. The card is configured with eight differential analog input channels and two analog output channels, each with 16 bits of resolution.

The scanning and data acquisition programs were written in LabView 4.0. We chose to use LabView over other programming languages for its relatively short learning curve and ease in construction of a graphical user interface for controlling the microscope and viewing the scan results.

The control program generates analog voltages that are output to the waveform rectifier and piezotube amplifiers to

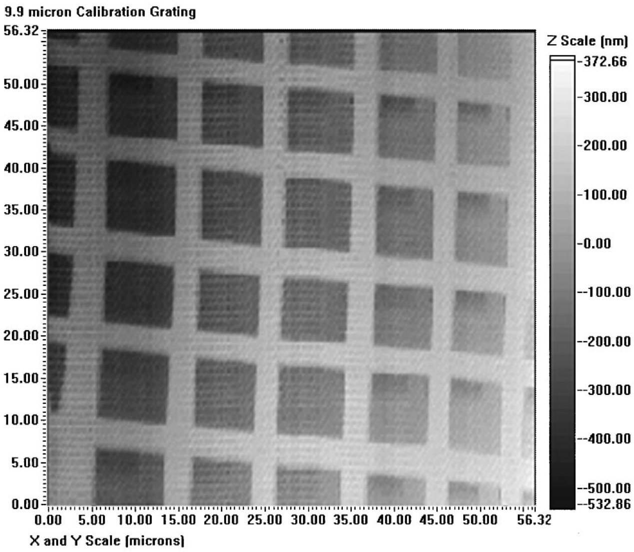

FIG. 8. Image of a 9.9 μm×9.9 μm reference grating taken with the BAFM.

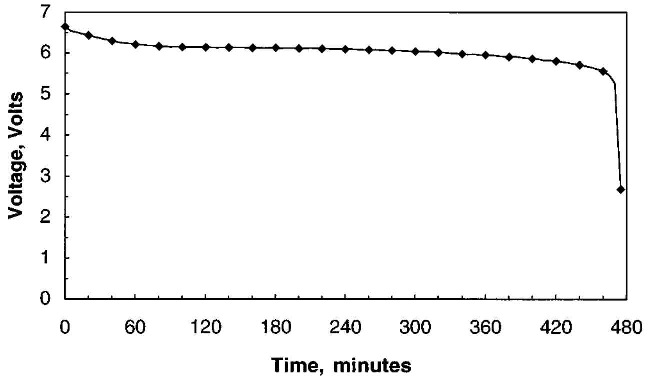

FIG. 9. Battery voltage vs time. The BAFM is capable of operating continuously for about 7 h using a Ni–Cd, 6 V, 2400 mA h camcorder battery before recharging is necessary.

produce an X-Y raster motion of the end of the tube. The X signal is a triangle wave whose frequency is determined by the user, usually between 0.5 and 4 Hz. The Y signal is a modified triangle wave whose frequency depends on the number of samples desired per scan and the frequency of the X signal. The modification to the Y signal allows the tube to scan in the positive X direction while the tube is held stationary in Y. Incremental motion in Y is performed when the tube scans in the negative X direction.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Scan results

In its present configuration, the prototype BAFM is capable of approximately a 53 μm×53 μm scan area. The 16-bit data acquisition card limits the maximum lateral resolution of the microscope to 8 Å, and the maximum vertical resolution to 12 Å. The actual vertical resolution is about 24 Å rms due to switching noise from the low-voltage dc-dc converter. We have yet to implement z servoing, so scanning is limited to the cantilever being in contact with the sample with the piezotube in constant height mode.

Figure 8 shows an image taken with the BAFM of a 9.9 μm×9.9 μm reference grating.

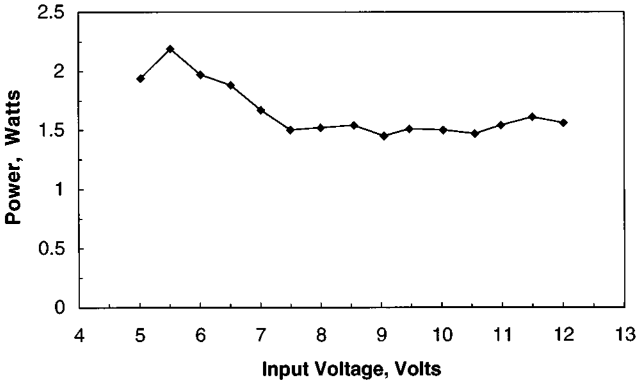

FIG. 10. Power consumption as a function of battery voltage. For a 6 V battery, the microscope uses about 1.8 W of power.

TABLE I. Power consumption of the various subsystems powered by the battery.

Subsystem	Power consumed (W)
High-voltage dc-dc converter	0.92
Low-voltage dc-dc converter	0.40
X-axis high-voltage amplifier	0.32
Y-axis high-voltage amplifier	0.15
Cantilever deflection amplifier	0.02
Total=	1.81

B. Power measurements

We analyzed the power consumption of the BAFM and found that it is capable of operating continuously for about 7 h on a single charge of the battery. Figure 9 shows the battery voltage versus time. We also looked at power consumption as a function of battery voltage. This test was performed by substituting an adjustable power supply for the battery, and varying the input voltage from about 5 to 12 V. Figure 10 shows that the microscope consumes between 1.5 and about 2.2 W over the indicated voltage range. It should be noted that the externally-powered waveform rectifier was not included in the above measurements. It consumes about 325 mW by itself.

Table I summarizes power consumption of the subsystems powered by the 6 V battery. The high-voltage dc-dc converter consumes approximately 920 mW, about half of the total. Losses in the diodes on the high-voltage side of the transformer constitute about half of the power lost in the high-voltage converter.

C. Future Improvements

There are many opportunities for improvement of the BAFM. For example, it would be desirable to use a data acquisition card or DSP with at least four analog outputs to drive the four tube quadrants independently, thus eliminating the need for the waveform rectifier. Resolution of the microscope would be improved if 20-bit A/D and D/A converters were used and if improvements were made to reduce noise from the low-voltage dc-dc converter. Portability of the system would be enhanced if the I/O boards were in PCMCIA format, so a laptop computer could be used.

We hope that the work described in this article will encourage further developments of self-contained scanning probe devices.

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