

Determination of nanosecond high-voltage pulse shapes at the surface of needle emitters*

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A method is described for determining, *in situ*, the shapes of nanosecond, positive high-voltage desorption pulses at the surface of a field-ion specimen, without the use of waveform-distorting probes or voltage dividers. In practice, a negative pulse known to be identical in shape to the positive desorption pulse is used to initiate field electron emission from the specimen surface. The resulting time-varying field emission current is recorded by a detector, and the Fowler–Nordheim equation is iterated to obtain the actual time-varying specimen potential. The pulse shape obtained can be used to predict accurately the arrival time of unknown surface species in time-of-flight atom-probe instruments, or to monitor the effect of changes in the pulse transmission line to the specimen. When applied to pulsed e-beam devices and flash x-ray machines, time-varying potentials at field-emission cathodes can be determined with nanosecond resolution.

INTRODUCTION

During the past eight years, a number of surface analytic instruments have been developed which combine the atomic resolution of the field-ion microscope with the single-particle detection capability of sensitive mass spectrometers. Several of these utilize time-of-flight analysis for species identification,^{1,2} with a high-voltage, positive pulse applied to the specimen to field-desorb surface species. Since the kinetic energy spread of the field-desorbed ions is affected by the shape of this pulse (which, therefore, affects the mass resolution in such instruments), a detailed knowledge of the time-dependent potential at the specimen surface during the desorption event is of great practical interest. Although energy spreads of several hundred eV have been measured³ for the desorbed ions, and attributed to the shape of the desorption pulse,⁴ no satisfactory procedure has yet been reported for precisely measuring the desorption pulse shape at the specimen surface. Frequently, a high-frequency oscilloscope probe is used to estimate the shape of the desorption pulse by determining the pulse shape on the transmission line to the specimen,⁵ or by direct connection to the specimen mount.^{6,7} However, the presence of the probe can distort the actual waveform so that the time-varying potential at the specimen surface *in its absence* cannot be unambiguously determined.

In this paper, the first *in situ*, noncontacting procedure for determining the shape of the nanosecond desorption pulse at the specimen surface is presented.⁸ This procedure will provide an accurate description of the time-dependent potential at the specimen surface

provided changes in specimen geometry, resulting from field desorption of surface atoms, can be neglected.

THEORY

Consider the production of identical species at a field-ion specimen surface resulting from an applied high-voltage pulse, with an abundance that depends upon the resulting electric field. Allow these particles to traverse a drift region between the specimen and a detector capable of recording their arrival. If the particles traverse the drift region in a time short compared to the rise time of the pulse applied to the specimen (and the detector has sufficient time resolution), the detector signal will accurately reflect the time evolution of species abundance at the specimen. Provided the species abundance is a known function of specimen potential, the detector signal can be converted, point by point, to an equivalent specimen potential, which will be the desired pulse shape at the specimen surface.

The success of such a method depends upon the ability of the particles to traverse the drift region quickly,⁹ and produce a signal whose amplitude depends upon the specimen potential in a known manner. Field-desorbed positive ions do not satisfy these criteria, but field-emitted electrons from negatively pulsed specimens will, since their abundance as a function of specimen potential can be accurately calculated from the well-known Fowler–Nordheim equation. Therefore, the shape of a negative pulse at the specimen surface can be determined after the constants in the Fowler–Nordheim equation have been evaluated. The shape of a positive desorption pulse can also be determined, pro-

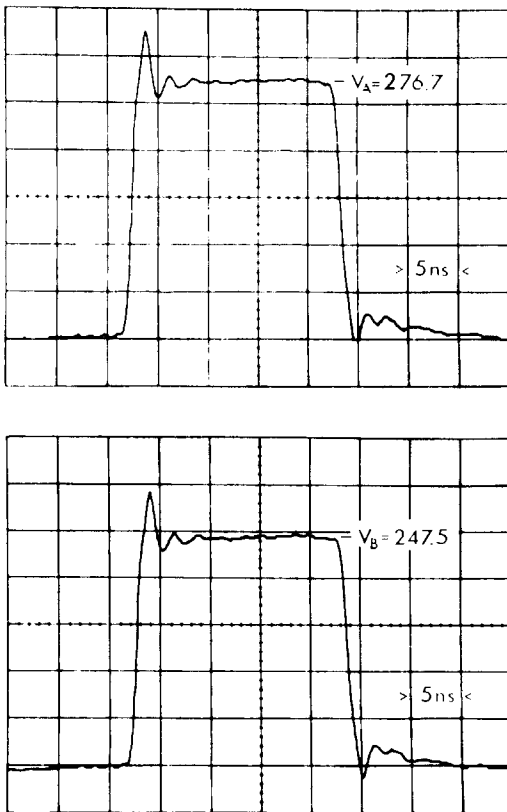


FIG. 1. Negative voltage pulses applied to a needle emitter (approximate radius = 300 Å) to initiate field emission. Recorded on the transmission line to the specimen with a Tektronix CT-3 pulse monitor and inverted, here, for clarity. Horizontal scale is 5 nsec/div. Vertical scale is 50.5 V/div. Waveform recorded with a Tektronix 2221 waveform digitizing system.

vided a negative pulse whose shape is known to be identical to the positive desorption pulse, can be generated. Usually, this is possible,¹⁰ and can be verified by observing the positive and negative pulse shapes at the same point on the pulse transmission line to the specimen.

METHOD

The Fowler–Nordheim equation¹¹ may be written

$$I = CV^2 \exp(-D/V), \quad (1)$$

where C and D are constants to be empirically determined, and I is the instantaneous current measured at the detector, corresponding to an instantaneous potential, V , applied to the specimen. C and D are usually determined from a plot of $\ln(I/V^2)$ vs $1/V$.¹¹ Here, an alternate approach is used which makes the explicit assumption that the pulse waveform at the specimen during emission differs from that measured at any point along the pulse transmission line to the specimen *only during the initial portion of the pulse*. Beyond this time (when the pulse amplitude reaches an essentially constant value), the specimen potential is assumed to be the normal pulse amplitude¹² as measured at any point along the transmission line to the specimen.

To understand this assumption, it is helpful to think of the voltage waveform at the specimen as being caused

by the superposition (at the emitter surface) of the initial pulse and multiple secondary pulses reflected from the impedance discontinuities encountered by the pulse as it travels to the specimen. Since these will damp rapidly with time, only the initial portion of the pulse at the specimen surface will differ significantly from that measured by conventional probes or voltage dividers along the pulse transmission line. For most atom-probe-like instruments, the major discontinuity in impedance usually results from the feedthrough and coupling capacitor which transmit the desorption pulse into the vacuum system. It is interesting to note that this impedance discontinuity may actually be an asset. If the impedance discontinuity results in an initial voltage overshoot, the temporal extent of the field-evaporation event will be limited and mass resolution may improve, a possibility suggested by Müller.¹³ The technique described in this paper provides the first opportunity to tailor the overshoot in the desorption pulse specifically for optimum mass resolution by optimizing this impedance discontinuity.

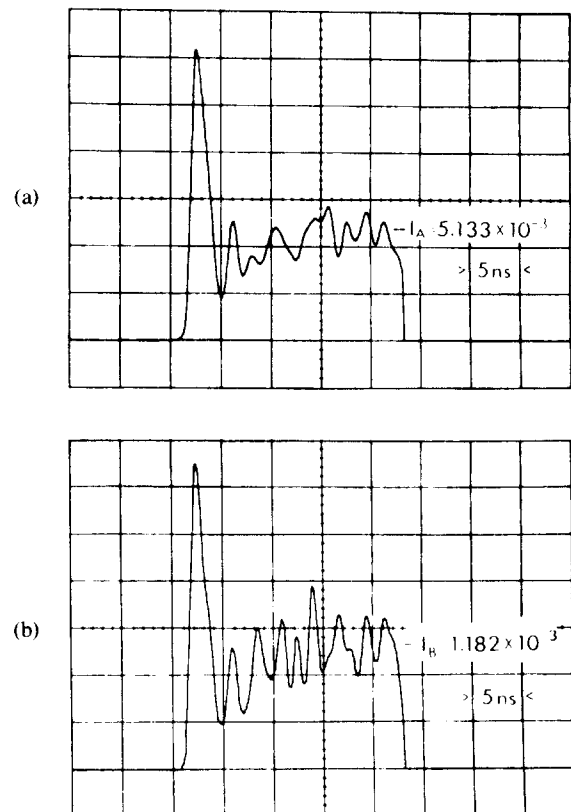


FIG. 2. (a) Field-emission current waveform recorded with a Tektronix 2221 waveform digitizing system. Spherical Chevron CEMA detector potentials: Input plate—930 V; second plate—1029 V; accelerating potential—3939 V. Horizontal scale is 5 nsec/div. Vertical scale is 2.2 mA/div. Baseline noise forced to zero following digitizing of CEMA output for all time $t \geq T$, where T is the half-width (at half-maximum) of the voltage pulse in Fig. 1 (top). (b) Field-emission current waveform recorded with a Tektronix 2221 waveform digitizing system. Spherical Chevron CEMA detector potentials: Input plate—930 V; second plate—1029 V; accelerating potential—3939 V. Horizontal scale is 5 nsec/div. Vertical scale is 0.44 mA/div. Baseline noise forced to zero following digitizing of CEMA output for all time $t \geq T$, where T is the half-width (at half-maximum) of the voltage pulse in Fig. 1 (bottom).

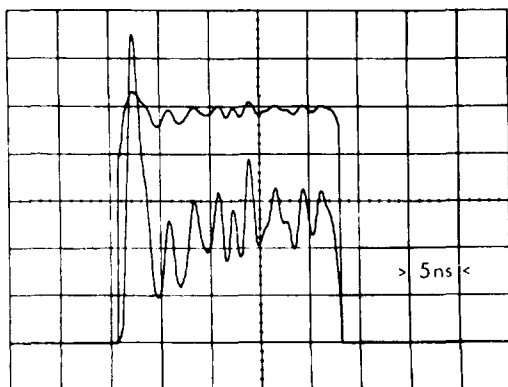


FIG. 3. Actual voltage waveform appearing at a field-ion specimen surface during field desorption, obtained using the method described in the text (upper trace). Average pulse amplitude, late in time, is the average amplitude (247.5 V), late in time, of the voltage pulse of Fig. 1 (bottom). The field-emission current waveform of Fig. 2(b) (lower trace) is reproduced for comparison. Horizontal scale is 5 nsec/div. Baseline of upper trace has been forced to zero outside of the desorption pulse by forcing the baseline noise of Fig. 2(b) to zero.

In order to determine the two unknown constants in Eq. (1), two voltage pulses of identical shape (but different amplitude) are applied to the specimen.¹⁴ In each case, the resulting emission current at the detector is recorded. Figure 1(a) is a typical voltage pulse as recorded by a pulse monitor¹⁵ on the transmission line to the specimen, with V_A defined as the average pulse amplitude late in the pulse. Figure 2(a) gives the resulting field-electron emission current, where I_A is the average current produced by the average potential, V_A . V_B and I_B are similarly defined for the waveforms of Figs. 1(b) and 2(b), respectively. Since the average potentials and currents of Figs. 1 and 2 are measured late in the pulse, they should correspond to the actual specimen potentials and field-emission currents related by the Fowler–Nordheim equation,

$$I_A = CV_A^2 \exp(-D/V_A), \quad (2)$$

$$I_B = CV_B^2 \exp(-D/V_B). \quad (3)$$

Solving Eqs. (2) and (3) simultaneously for the unknown constant yields

$$D = \frac{\ln(I_A V_B^2 / I_B V_A^2)}{1/V_B - 1/V_A} \quad (4)$$

and

$$C = \frac{I_A}{V_A^2 \exp(-D/V_A)}. \quad (5)$$

From the average potentials, and currents, of Figs. 1 and 2, C and D can be evaluated:

$$C = 2.6 \times 10^{-3} \quad \text{and} \quad D = 2.9 \times 10^3.$$

Using these values, Eq. (1) can be iterated, point by point, along the emission current waveform of Fig. 2(b) to obtain the actual voltage waveform at the specimen. The result, after normalization, is shown in Fig. 3 together with the emission current waveform of Fig. 2(b). Since the negative voltage pulse used to obtain this

waveform is known to be identical in shape to the positive desorption pulse whose shape is desired, Fig. 3 also gives the shape of the positive desorption pulse at the specimen surface. The amplitude at any point on the normalized voltage pulse of Fig. 3 can be determined by scaling, since the nominal pulse amplitude, late in time, is assumed to be equal to V_B (247.5 V) of Fig. 1(b).

In order to ensure accurate current measurements, small-amplitude negative pulses were used to initiate field emission¹⁶ and the Channel Electron Multiplier Array detector gain was set to a nominal value (10^7) sufficient to record the arrival of individual electrons. This ensured that CEMA saturation would be eliminated, and changes of the specimen surface (due to excessive field emission or ion bombardment) would be minimized.

By time gating¹⁷ the CEMA detector and observing the temporal extent of arriving positive ions, the temporal duration of the actual field-desorption event can be estimated. For the positive desorption pulse of Fig. 3, and conditions of gentle field evaporation of rhodium ions (Rh^{2+}) at 10^{-10} Torr, it has been observed that changing the delay of the CEMA gate pulse by ± 2 nsec resulted in complete elimination of the Rh^{2+} image spots on the detector. This indicates that the maximum duration of the desorption event is approximately 4 nsec, in agreement with the width of the initial voltage overshoot shown in Fig. 3. In addition, applying a standard calibration procedure¹⁸ to the imaging, field-desorption mass spectrometer¹⁷ (in which the time-gated measurements were made) resulted in a value of the effective desorption pulse amplitude, αV_p ,¹⁹ equal to the scaled maximum of the initial voltage overshoot shown in Fig. 3. These two independent measurements confirm the ability of the field-emission method to determine accurately the actual time-varying potential at the specimen surface during field desorption.

The desorption pulse waveform, now measurable, can be used instead of idealized desorption pulse shapes in previously published calculations²⁰ to obtain an accurate measure of the energy spread observed for field-evaporated ions. Alternately, accurate travel times can be calculated for the field-desorbed ions, permitting accurate species identification to be made in time-of-flight instruments.

An obvious extension of the method reported here is the determination of the pulse shape appearing on field-electron-emitting cathodes in pulsed e-beam devices or flash x-ray machines. By inserting a suitable detector in front of the anode in such devices (or using the anode itself if the current density is large enough), time-varying cathode potentials can be determined with nanosecond accuracy. This would minimize the need for voltage dividers which are difficult to construct, or provide an accurate calibration for those which must be present.

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- ¹ E. W. Müller, J. A. Panitz, and S. B. McLane, *Rev. Sci. Instrum.* **39**, 83 (1968).
- ² J. A. Panitz, *Rev. Sci. Instrum.* **44**, 1034 (1973).
- ³ S. V. Krishnaswamy and E. W. Müller, 20th Field Emission Symposium (University Park, PA, 1973).
- ⁴ E. W. Müller, *Lab. Prac.* **22**, 408 (1973).
- ⁵ J. A. Panitz, 22nd Field Emission Symposium (Atlanta, GA, 1975).
- ⁶ J. A. Panitz, Ph.D. thesis (Pennsylvania State University, 1969).
- ⁷ H-O. Andrén and N. Nordén, 22nd Field Emission Symposium (Atlanta, GA, 1975).
- ⁸ One of us (R.J.W.) wishes to acknowledge a discussion of the pulse measurement problem with E. W. Müller in 1973.
- ⁹ The species produced at the specimen must traverse the drift region quickly (in a time short compared to the pulse rise time) to ensure that the detector signal will not be broadened by their arrival time distribution.
- ¹⁰ Positive desorption pulses are usually generated by a cable-discharge pulse generator employing a fast mercury switch. Reversing the polarity of the cable-charging potential produces an identical pulse of opposite polarity.
- ¹¹ R. Gomer, *Field Emission and Field Ionization* (Harvard U. P., Cambridge, MA, 1961), p. 30.
- ¹² For cable-discharge pulse generators terminated in their characteristic impedance, the nominal pulse amplitude will be one-half of the cable-charging potential.
- ¹³ E. W. Müller, *Ber. Bunsenges.* **75**, 979 (1971).
- ¹⁴ Here, only two voltage pulses (and resulting field-emission current waveforms) were used to determine the Fowler–Nordheim constants, C and D . Generally, this has proved to be adequate for most pulse shape determinations. Greater accuracy can be achieved by using several voltage and current waveforms and a least-squares determination of C and D .
- ¹⁵ Tektronix model CT-3.
- ¹⁶ It can be seen in Fig. 3 that a relatively small voltage overshoot at the beginning of the pulse results in a considerably larger current overshoot due to the exponential form of the Fowler–Nordheim equation. It is therefore necessary that the amplitude of the pulse overshoot be kept as small as practicable to prevent emission currents due to such voltage overshoots from completely dominating the current measurements. This can be accomplished by superimposing the pulse on a dc bias such that the nominal pulse amplitude is a small fraction of the total voltage applied to the specimen.
- ¹⁷ J. A. Panitz, *J. Vac. Sci. Technol.* **11**, 206 (1974).
- ¹⁸ J. A. Panitz, S. B. McLane, and E. W. Müller, *Rev. Sci. Instrum.* **40**, 1321 (1969). The second of the two calibration procedures described was used for this study.
- ¹⁹ Here, α is the usual “pulse factor” (see Ref. 18), and V_p is the nominal pulse voltage, taken to be equal to one-half of the pulse-forming cable voltage (see Ref. 12).
- ²⁰ S. V. Krishnaswamy and E. W. Müller, *Rev. Sci. Instrum.* **45**, 1049 (1974).