Ultra Short and High Voltage Pulse Shaping for Atom Probe Tomography Improvement

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Abstract— Improvement of atom probe tomography technique requires the use of high voltage rectangular pulses on a sample inside an ultra-high vacuum chamber. In this paper, we present a rectangular ultra-short pulse generator using photoconductive semiconductor switch and microstrip technology. It can deliver the pulsed signal with rise time of about some picoseconds and full width duration less than nanosecond. The performances of the devices are compared to theoretical predictions.

1. INTRODUCTION

The technique of atom probe tomography is now widely used in the analysis of materials at the atomic level. The basic principle of the technique is the atom by atom erosion of needle-like sample by the physical mechanism of field evaporation. As shown in Figure 1, the intense electric field at the sample surface is produced by means of high voltage pulses superimposed on the standing voltage. Ion emission is triggered by the voltage pulse and ion flight time is measured by calculating the delay time between the departure time(the triggering time) and the arrival time on a position sensitive detector. The accuracy of the measurement of flight times will contribute to the mass resolution of this instrument. Due to the stochastic nature of the field evaporation process, this can cause different ions of the same isotope leave the sample around the peak voltage(at the triggering time), and therefore acquire slightly smaller kinetic energy(and hence slightly slower velocities) comparing to ions evaporating at the peak voltage. This effect degrades significantly mass-resolving power.

To overcome this shortcoming, modern atom probe(LEAP [2]) integrates an energy compensation device to reduce the impact of energy spread of ions. But these devices [3] generally reduces the detection efficiency of the atom probe. In this paper, we propose a new method to reduce the relative amount of ions with energy deficits. Section 2 explains how the ultra short rectangular

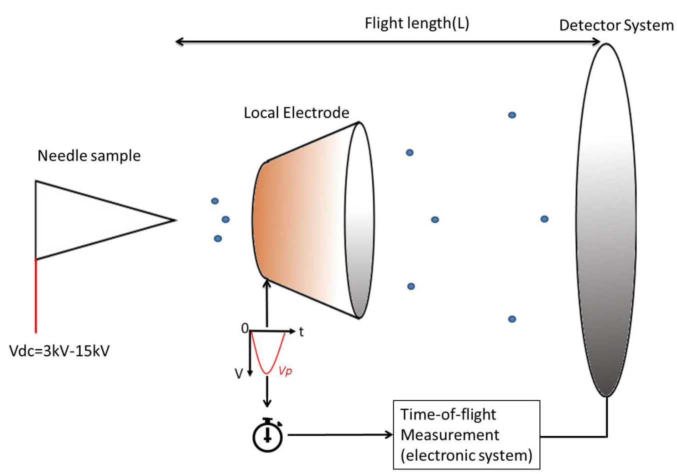


Figure 1: Schematic representation of a typical atom probe tomography. A local-electrode is an aperture (the diameter is about 40–100 μm) [1] placed close to the tip at a few micrometers. Atoms on the surface of needle-like specimen are stripped by the high electric field at a known time and are accelerated to the local-electrode. A position-sensitive detector records the striking positions of ions and time of flight of ions from the sample to the detector.

pulse improves the mass resolution, Section 3 describes the pulse generator based on photoconductor switch, Section 4 shows the experimental setup and the primary results verifying the proposed method.

2. CALCULATION OF MASS RESOLUTION DEGRADATION

In a simple approach, it is assumed that ions acquire instantaneously all the potential energy $E = neV$ (we will not consider dynamic effects in this approach) where V is the total voltage between the sample and the local electrode, ne is the charge of ion, the time of flight is seeing t_{flight}:

$$\frac{1}{2} m \left(\frac{l}{t_{flight}} \right)^2 = neV \tag{1}$$

where l is the total flight distance. The mass to charge ratio is given by:

$$M = \frac{m}{n} = 2eV \frac{t_{flight}^2}{l^2} \tag{2}$$

Field evaporation(the physical phenomenon inducing the atom by atom erosion) can be modeled by an Arrhenius expression. The rate of evaporation K_{hr} (the number of atoms evaporated per second) is written as:

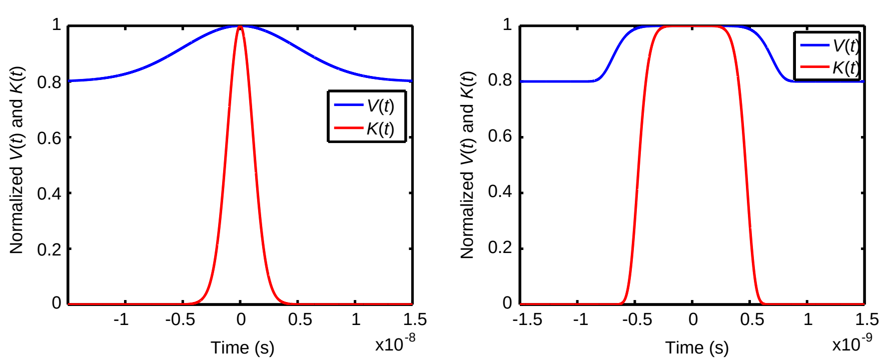
$$K_{hr} = A_{hr} \exp\left(-\frac{\frac{V_0 + V_p(t)}{V_e}}{K_B T} \right) \tag{3}$$

Where A_{hr} being the field evaporation rate-constant pre-factor for high risk atoms, k_B the Boltzmann factor, T the temperature, and V_e the field evaporation activation energy. We refer the reader to the book of Miller and Forbes [4, Chapter 3] for a detailed explanation of Eqs. (1) and (3). Figure 2 presents different evaporation rates as a function of pulse shape. The maximum rate of evaporation $K_{\max}$ occurs at the peak of the pulse $V_{\max} = V_0 + V_{p\max}$, with V_0 the standing voltage applying on the sample, and $V_{p\max}$ is the maximum value of the voltage pulse. The evaporation rate can be given by:

$$\frac{K(t)}{K_{\max}} = \exp\left(-\alpha \left(1 - \frac{V_p(t)}{V_{\max}} \right) \right) \tag{4}$$

where $\alpha = \frac{1}{K_B T}$, T the temperature and K_B the Boltzmann's constant.

In standard atom-probe design, field evaporation is triggered by nanosecond pulse that can be modeled with a Gaussian profile as shown in Figure 2(a). Figure 3 shows that the Gaussian profile (red curve) induced the significant energy deficits. But, using a rectangular pulse shown as Figure 2(b), the energy deficits of ions can be reduced by a factor 10, i.e., rectangular pulses reduce the range of the ion energy distribution. This above analysis has provided that a rectangular pulse is needed to improve mass resolution.



(a) (b)

Figure 2: The voltage pulse profile (blue line) as a function of time and the corresponding evaporation rate $K(t)$ (red line) are plotted.

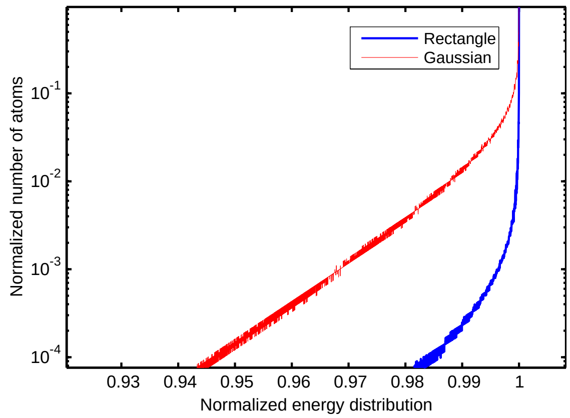


Figure 3: The normalized number of atoms as a function of ion energy distribution for different pulse shapes

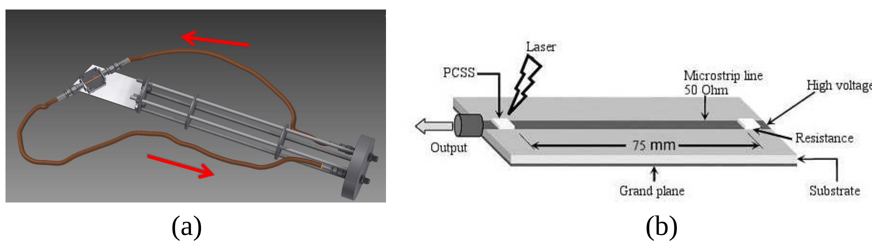


Figure 4: (a) illustrates the schematic representation of the transmitting system. The local electrode is connecting with two SMA cables, another ends of which connect to input/output connector in the flange. (b) shows that the schematic diagram of a pulse generator with microstrip technology. Circuit trace on microstrip printed circuit board (PCB) is designed for pulse duration of 1 ns and characteristic impedance of 50 Ω with FR4 subtract. The output of the pulse generator is connected to the input of the transmitting system.

3. PULSE GENERATOR USING PHOTO-CONDUCTIVE SEMICONDUCTOR SWITCH (PCSS)

Photo-Conductive Semiconductor Switches (PCSSs) have been widely used in high voltage ultra-short pulse technologies since Auston et al. [5] first presented the optoelectronic switching in silicon. PCSS offers unique features for generating kilovolts pulses with rise time in picoseconds or nanoseconds scale, such as jitter-free response and high breakdown voltage [6–8]. There are two switching regimes of PCSSs: linear and avalanche regime. In the latter case, despite very low optical energy is required for efficient switching, the avalanche switching reduces strongly the switch lifetime. Additionally, it increases the temporal jitter response. The linear switching regime, PCSS can work without jitter at a kilohertz repetition rate. The linear mode ensures a long lifetime of our application with minimum temporal jitter. Embedding optoelectronic switching of silicon semiconductor in microstrip transmission-line structure, we can produce square, picoseconds pulses [7]. The microstrip line is charged by a high voltage through a large resistance limiting the current and the other termination is connected to an adapted resistance (R_L) through the PCSS. The output voltage (V_{out}) is given by:

$$V_{out} = V_{dc}\frac{R_L}{2Z_0 + R_{on}(t)} \tag{5}$$

where V_{dc} is the bias or charging voltage, R_{on} is the resistance of PCSS controlled by laser energy, Z_0 is the characteristic impedance of the transmission line. In order to obtain optimal output, we have to minimize the value of R_{on} and make sure $R_L = Z_0$.

4. EXPERIMENTAL SETUP AND RESULTS

A schematic representation of the pulse generator is illustrated in Figure 4(b). A transmission line is capacitive energy storage element charged by a high voltage DC power supply [9]. An optical command controls the photoconductive switch to delivery of the stored energy into the load. The

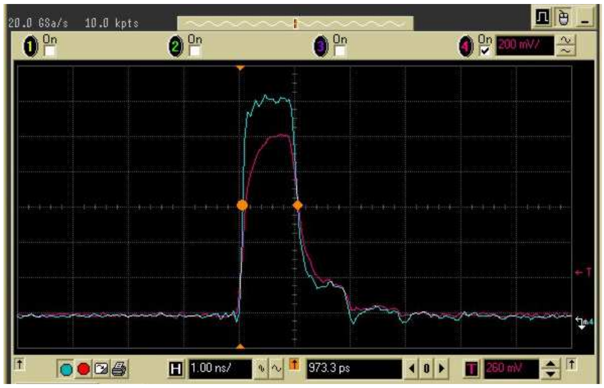


Figure 5: Experimental result: the pulse generator configuration is illustrated in Figure 4(b) with Silicon rectifier diode. This voltage pulse is obtained with the energy of optical command about 30 μJ (per pulse). The rise time is shorter than 100ps and the full width at half maximum is about 1ns.

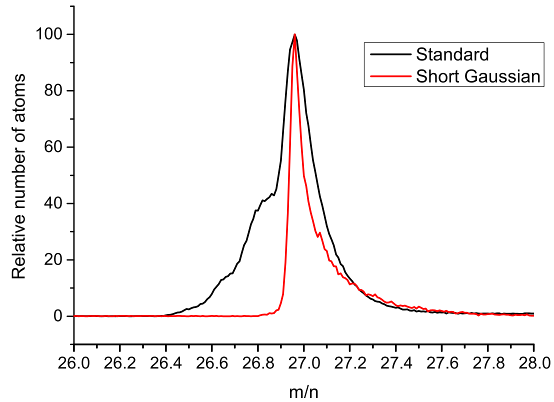


Figure 6: Typical aluminum mass spectra obtained in atom probe: the preliminary analysis was obtained with two pulses. For a standard pulse, mass resolutions were measured to be 180 FWHM; for a Gaussian pulse with a duration of 1ns, mass resolutions were measured to be 520 FWHM.

pulse duration depends on the transmission line length and the amplitude can be obtaned by Eq. (5).

We use the high-voltage rectifier diode sustaining up to 4 kV DC as PCSS. The 'open' switch state is equivalent to a very high resistance which can be operated by varying the energy of the optical command (Laser beam). The switch will transform to 'closed' state when the switch acquires adapted optical energy. For the 800 nm wavelength of the optical command, 20 μJ is needed to operate efficiency switching. An amplified Ti : Sa femtosecond laser (Quantronix Integra-E) with an average power up to 2 W is used as the optical command. It can deliver optical pulse at 800 nm with a repetition rate of 1 kHz.

In Figure 5, the quasi-rectangular pulse (blue) was measured at the output of the pulse generator. This voltage pulse will be sent into atom probe analysis chamber (ultra-high vacuum) and return to the oscilloscope thanks to the transmitting system shown in Figure 4(a). So we can directly observe the pulse shape (red line in Figure 5) which is applied on the sample. Figure 5 demonstrates that the system acts a comportment as 'Low-pass filter' which removes the undesired part(the oscillation on the top of the pulse). At the same time, the further loss of amplitude occurs (∼20%). The voltage pulse applied to the sample is thus a Gaussian-similar pulse. The rise time of the signal(blue one in Figure 5 is less than 100 ps due to the fs optical command, however, because of the bandwidth limitation of measurement device, we are not able to observe a 'real' pulse.

Preliminary mass spectrum obtained by analyzing Aluminum sample ($M = 27$ uma) with standard voltage pulses (∼ 10 ns width duration) and with short pulses (700 ps width duration) demonstrates a significant improvement of the mass resolution power. Comparing to the standard atom probe, the mass resolution is generally improved by a factor 3 (Figure 6).

5. CONCLUSION AND PROSPECTIVE

We have proposed and developed a new method to improve the performance of atom probe tomography based on photoconductive switch. The preliminary result shows that a ultra short Gaussian pulse can improve the mass resolution of atom probe. We have designed different pulse generators which can now be used to investigate the combined effect between the pulse duration and the distance of tip-to-electrode on mass resolution. The distance of tip-to-electrode has great influence on the mass resolution [10]. In future work, we will characterize the transmitting system by Network Analyzer. To avoid low pass filter, 'in-situ' setup is under work. The generated ultra short high voltage will be applied directly to the sample.

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