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Novel method for the production of finely spaced Bradbury–Nielson gates

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Bradbury–Nielson gates for the modulation of beams of charged particles, particularly ion beams in mass spectrometry, have been produced with an adjustable wire spacing down to 0.075 mm. The gates are robust, they can be fabricated in less than 3 h, and the method of production is reproducible. In time-of-flight mass spectrometers, fine wire spacing leads to improvements in mass resolution and modulation rates. Gates that were produced using this new method have been installed in a Hadamard transform time-of-flight mass spectrometer in order to demonstrate their utility. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1416109]

I. INTRODUCTION

For many experiments, it is necessary to deflect the trajectory of a beam of charged particles. One of the most convenient methods for accomplishing this task is to use an interleaved comb of wires, which is called a Bradbury–Nielson gate (BNG). A BNG consists of two electrically isolated sets of equally spaced wires that lie in the same plane and alternate in potential. When no potential is applied to the wires relative to the energy of the charged particles, the trajectory of the charged particle beam is undeflected by the gate (Fig. 1). To deflect the beam, bias potentials of equal magnitude and opposite polarity are applied to the two individual wire sets. Deflection produces two separate beam profiles, each of whose intensity maximum makes an angle α with respect to the path of the undeflected beam. In this manner it is possible to modulate or gate ion beams in a controlled fashion.

Bradbury–Nielson gates were first developed as electron filters in 1936.[1] Recognizing that these gates had a much smaller effective field size than the commonly used deflection plates, Weinkauf[2] and co-workers began in 1989 to use BNGs for modulating ion beams in time-of-flight mass spectrometry (TOF-MS). Since that time, many groups[3–5] have reported similar use. A common application is mass-to-charge (m/z) selection in TOF-MS.[3] Ions are allowed to drift before reaching the gate where short "on pulses" allow only ions of a selected m/z to pass. Tandem configurations, where the rising and falling edges of the ion packets are created by two different BNGs, have been described as a way to improve mass resolution for m/z selection.[6] Use of BNGs is also common in ion mobility mass spectrometry, where the gates regulate the injection of ion packets into the drift tube.[7–10]

An extremely demanding application for these gates is Hadamard transform time-of-flight mass spectrometry (HT-TOFMS).[4,5] This application has motivated our efforts to produce improved BNGs, and the characterization of our BNG is related specifically to this use. In HT-TOFMS, the ion beam is modulated with a pseudorandom sequence of "on" and "off" pulses by applying the corresponding modulation to a Bradbury–Nielson gate. Typical modulation rates are on the order of 10 MHz, with rise times of about 10 ns and modulation voltages of 10–50 V with respect to the voltage of the ions, called the liner voltage (~1 kV). After the pseudorandom sequence is applied, the ion packets created by the on/off modulation interpenetrate one another as they drift through the flight tube. The detected signal is a convolution of the mass spectra corresponding to these packets. Using knowledge of the applied pseudorandom sequence, this signal is deconvoluted to yield a single mass spectrum. The integrity of the deconvolution is dependent on the profile of the applied pulses and the discreteness of the sequence felt by the ions. Ions that are improperly modulated because of spatial and energetic ambiguities at the gate will be observed as noise after deconvolution of the detector signal. Such ambiguities can result if: (1) ions travel too slowly or the effective modulation region is too long and consequently ions are affected by multiple on/off pulses; and (2) rise times and noise destroy the square shape of a pulse, corrupting the binary nature of the modulation. As in any experiment using Bradbury–Nielson gates to shutter ions, the resolution of a HT-TOFMS is dependent on the modulation speed. On and off pulses applied to the gate have finite durations. At best, mass spectrometers can only resolve ions having flight times differing by times greater than the duration of these pulses. Likewise, when using an ion gate for m/z selection, the mass resolution of the gate is dependent on how rapidly the gate can switch the beam on and off. The mass resolution of a Bradbury–Nielson gate is thus dependent on how fast the necessary voltage can be applied to the wires and on the effective area of the electric field producing the modulation.

The first determinant of modulation rates is the electronics used. The circuitry used in HT-TOFMS allows application of on/off sequences with element widths between 40 and 200 ns.[11] In order to produce square pulses, rise times must be small compared to these bin widths. The rise time of a pulse, arising from capacitive effects, is proportional to its voltage. It is anticipated that as wire spacing is reduced,

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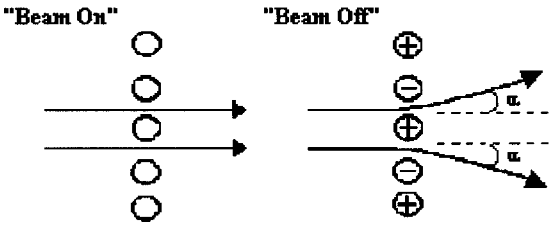

FIG. 1. The operation of a Bradbury–Nielson ion gate. In the "beam on" mode, the wires of the gate are held at the liner voltage of the instrument. Ions are unaffected by the gate, and pass undeflected. In the "beam off" mode, a bias voltage of equal magnitude and opposite sign is applied to the two isolated wire sets. Attraction toward one polarity and repulsion from the other yields a net deflection of the ions from their initial path. An ion's actual angle of deflection may vary from α, depending on its position relative to the two wires it passes between.

smaller voltages will be required to achieve a given deflection angle. Thus, reductions in wire spacing allow faster modulation speeds.

Ideally the width of the modulation field in the direction parallel to the flight path would equal the diameter of the wires composing the gate. In this case, the fate of an ion would be determined as it crossed the plane of the gate. Simulations by other investigators[4,6] predict that the effective field produced by a Bradbury–Nielson gate actually extends along the normal to the plane of the gate a distance on the order of $0.80d$, where d is the spacing between adjacent wires. Finer spacing between adjacent wires allows better time resolution when gating or modulating the ion beam because of the corresponding decrease in the longitudinal extension of the deflection field perpendicular to the plane of the gate. Given that in TOF experiments the flight time is proportional to the square root of an ion's mass-to-charge ratio, this temporal resolution translates to the mass resolution of a TOF mass spectrometer. In the special case of HT-TOFMS, the validity of the deconvolution also depends on the temporal accuracy of the modulation. Discrepancies between the intended sequence and applied sequence lead to artifacts referred to as masking errors.[12]

In order to improve mass resolution and modulation pulse profiles, much effort has been made to produce Bradbury–Nielson gates with minimal spacing between wires. A detailed description of the use of this device in time-of-flight mass spectrometry appeared in 1995 by Vlasak *et al.*[3] In this work, a wire spacing of 1 mm was achieved by weaving a wire through holes on two separate frames and applying tension with a bracing screw between the two frames. A significant reduction of the wire spacing to 0.5 mm was reported in 1998 by Stoermer *et al.*[6] who used the grooves on two nylon threads to control the wire spacing. As previously mentioned, this group used two sequential grids to minimize pulse widths. Still, they concluded that further reduction in wire spacing would improve m/z selectivity in TOF experiments.

The next advance in the reduction of wire spacing was reported by Brock *et al.*[4,5,11] who were able to construct Bradbury–Nielson gates for their HT-TOF mass spectrometer with a wire spacing of 0.16 mm, working by hand under a microscope to set the wires in a silicon-etched frame. This procedure[11] was extremely laborious, requiring several days to complete the assembly of a single gate. Furthermore, the frames were expensive and the quality of the fabricated grids was inconsistent.

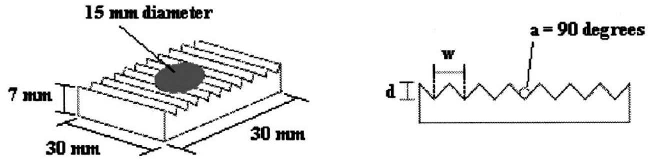

FIG. 2. The polymer wire guides. Evenly spaced grooves are machined in blocks of the low-vapor pressure polymers PEEK and Ultem 1000. All grooves have an interior angle of 90°. Space between grooves w is adjustable, and groove depth d is maximized at any w. A 15 mm hole is drilled through the block for passage of the ion beam.

Here, we report on a method that allows production of Bradbury–Nielson gates with wire spacing as small as 0.075 mm, which can be carried out in 3 h and which is readily adjustable. Moreover, our method is easily automated. Instead of using etched silicon, we use synthetic polymers with controlled groove spacing and profile. The grooves are produced using a machining process. Our greatly improved speed of assembly is achieved by using a hand-cranked weaving tool that feeds one continuous wire into the grooves. The alternating (positive and negative) sets of wires are wound separately and attached to electrically isolated contacts on the frame using epoxy adhesive.

II. DESCRIPTION OF ASSEMBLY PROCESS

The first attempts at producing the grooves involved stamping a heated sheet of polyvinyl chloride (PVC) with a machined metal stamp possessing the reverse image of the grooved pattern. Although the method was successful, concerns about the homogeneity of the grooves and the volatility of PVC in the vacuum chamber necessitated the development of a more reliable technique.

In the current method, we machine grooves with an interior angle of 90° in the surface of a 38 mm ×38 mm × 7 mm block of the polymer polyether ether ketone (PEEK) (Boedeker Plastics, Shiner, Texas) or Ultem® 1000 (poly ether imide Boedeker Plastics, Shiner, Texas) (Fig. 2). The space between adjacent grooves is adjustable, with a minimum value of 0.075 mm and a maximum error at any spacing of 0.005 mm. For a given spacing, groove depths are maximized. When grooves are spaced by 0.075 mm, the maximum depth is 0.050 mm. Error in depth is estimated to be no more than 0.005 mm. A centered, 15-mm-diam aperture for passage of the ion beam is drilled in the polymer, normal to the grooved surface.

Figure 3 presents the stages of Bradbury–Nielson gate assembly. The machined polymer is mounted on the insulated face of an H-shaped portion of single-sided copper-clad circuit broad (outer dimensions are 60 mm × 60 mm and the interior cross bar has length 40 mm and width 30 mm [Fig. 3(A)]) with the grooves running from the top to the bottom of the H [Fig. 3(B)]. All polymer–copper-clad contacts are fixed using epoxy (ITW Devcon Corp. Danvers, MA).

Two small portions of single-sided copper clad (30 mm × 4 mm) are fixed on the bottom side of the polymer (op-

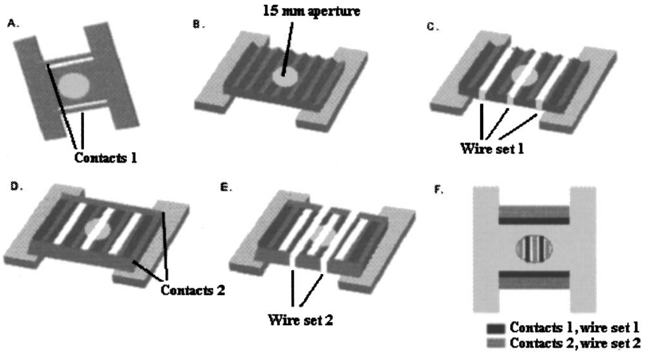

FIG. 3. Assembly of the Bradbury–Nielson ion gates. (A) H-shaped portion of single-sided copper clad with center through hole and two isolated copper contacts. (B) Machined polymer fixed on insulated face of circuit board frame. (C) Wire set 1 wound through alternating grooves. (D) Contacts 2 fixed on ends of polymer portion, copper side facing out. (E) Wire set 2 wound between wires of set 1. (F) View of gate from copper face of circuit board frame. Both wire sets have been cut on this side of frame.

posite the grooves) in the region where the block extends over the center bar of the H-shaped copper frame. These pieces serve as the contacts for wire set 1.

The assembled piece is mounted on a hand-cranked rotating screw within a homebuilt weaving instrument. A schematic of this device is presented in Fig. 4. 20-μm-diam gold-plated tungsten wire (California Fine Wire Co., Grover Beach, CA) runs from its spool over a directing screw, which is coupled to the hand-cranked screw by a belt, to the copper frame. The end of the wire is fixed to either of the mounted contacts using epoxy. A 40 g weight is hung from the wire, between the directing screw and the spool, in order to provide a constant tension on the wire. Beginning on one side of the center hole, the hand crank is turned, rotating the frame and drawing thread from the spool at approximately 2 cm/s. While watching through a microscope, wire set 1 is guided into alternating grooves on the surface of the polymer and around the frame [Fig. 3(C)], touching both contacts on each pass. As the hand crank is turned, the threads of the directing screw guide the wire from one side of the frame to the other, across the width of the aperture. Wire position and frame position are adjusted to optimize wire/groove alignment. After winding the wire across the entire width of the opening, the wire is bound to both copper contacts using epoxy. Once secure, a razor blade is used to remove the segment of the wire between the two contacts on the side of the frame opposite the polymer.

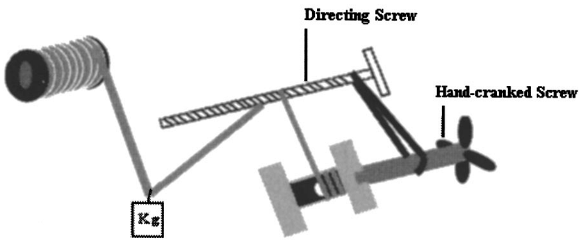

FIG. 4. The weaving instrument. 20 μm gold-plate tungsten wire is fed from the spool, over the directing screw, and to the frame. The wire is bonded to contacts on the frame using epoxy. A 40 g weight is hung from the wire to maintain tension. As the hand crank is turned, the frame rotates, wire is fed continuously from the spool, and wire is guided across the frame by the directing screw that is coupled to the hand crank by a timing belt.

Two pieces of the circuit board are glued directly to the faces of the polymer block at the ends of the grooves [Fig. 3(D)]. The copper side faces out and the insulted side of the board covers segments of wire set 1. These pieces serve as the contacts for wire set 2. Using the same procedure as used for wire set 1, wire set 2 is wound through the grooves between the wires of set 1 [Fig. 3(E)]. Again, the wires are cut, leaving wire only on the polymer side of the frame. Figure 3(F) shows a view of the frame looking from the copper side of the frame. The dimensions of the described BNG frame and aperture match the specific requirements of a HT-TOFMS. The proposed method can be used for other customized geometries by modifying the dimensions of the components.

III. RESULTS

Using this technique we have fabricated Bradbury–Nielson gates of 0.150, 0.100, and 0.075 mm between adjacent wires. The method works equally well at each of these scales. An ion gate with 0.150 mm wire spacing wound on an Ultem® 1000 frame has been installed in a HT-TOF mass spectrometer.

Experiments were conducted in the HT-TOFMS to demonstrate the deflection efficiency of the new BNG. In these experiments, ions were accelerated with −1250 V. With no modulation applied, wire sets 1 and 2 were held at bias voltages of −1285 and −1215 V, respectively, leading to constant deflection of the ion beam. To modulate between deflected and undeflected modes, pulses with magnitudes of 35 and −35 V were simultaneously applied to wire sets 1 and 2, respectively. These pulses brought both sets of wires to the liner voltage (−1250 V). The beam is deflected off the axis of its initial trajectory when the wires are at their bias volt-

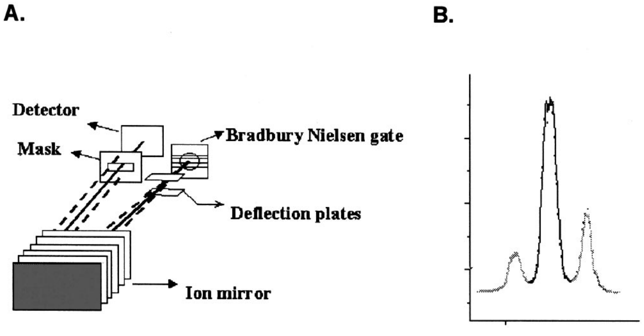

FIG. 5. (A) Schematic of the deflection and drift regions of the HT-TOFMS. (B) A three-beam profile displaying the two modes of the ion beam. The central, ''beam on'' peak is observed when both wire sets of the gate are held at a voltage equal to the liner voltage of the instrument, which is represented by the solid line in (A). The smaller peaks to each side are observed when the wire sets sit at bias voltages above and below the liner voltage, which is represented by the dashed lines in (A). This profile was acquired by using the deflection plates to sweep the focus of the three beams across the detector while simultaneously applying an on/off modulation to the beam. In practice, the detector is centered on the middle peak. Ions in packets that are not deflected reach the detector, whereas deflected ions miss the detector.

ages (−1285 and −1215 V), and the beam passes undeflected when both are at the liner voltage, −1250 V.

Figure 5(A) shows a schematic of the experiment. At standard operational deflection plate voltages, the undeflected beam (solid line) passes through the mask and hits the detector, while the deflected beams (dashed lines) are blocked. By varying the voltage in the deflection plates while applying the modulation, the three beams were each steered across the mask opening. The result is shown in Fig. 5(B). Complete resolution of the ‘‘beam on’’ (center peak) and ‘‘beam off’’ (side peak) modes was achieved with the new BNG. The voltage of the deflection plates was adjusted manually, leading to the slight lack of symmetry in the profile.

The 0.150 mm gate used for these experiments has been used for over 5 months without any complications or degradation of the materials. Liner voltages between 1050 and 1750 V and modulation voltages between 5 and 50 V have been applied with no detectable aging of the modulator.

With wire spacing as small as 0.075 mm, immediate improvements are expected in mass resolution for TOF measurements and temporal resolution for beam encoding. This decrease in wire spacing will also make possible the use of lower modulation voltages, leading to improvements in rise times of modulation pulses. Experiments are underway to quantify these effects in a HT-TOF instrument.

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