Stepwise and Hysteretic Transport Behavior of an Electromechanical Charge Shuttle

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Charge transport by way of objects that jiggle is a curious phenomenon. Here we present experiments on an electromechanical charge shuttle that reveal interesting electronic transport properties and rich dynamics. The current-voltage characteristics display distinctive jumps and hysteresis which reflect the influence of the vibrational environment on shuttle dynamics. These results provide fundamental guidance toward the understanding of transport phenomena in future electromechanical nanosystems and engineered microdevices.

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Electron transport through a nanoscopic "island" of unoccupied electron states is a fundamental topic of modern nanoelectronics research. Quite often the island is a metal, but in other instances it may be a quantum dot, or even a molecular orbital. Recently, it was proposed that the electron transport properties of such a system will be dramatically altered if the island is able to *move* and thereby facilitate electrostatic "shuttling" of charge [1]. The most basic configuration of a charge shuttle involves a movable metal island—the "shuttle"—situated between two electrodes held at a potential difference V (Fig. 1). As the shuttle comes into contact (direct or tunneling) with an electrode, it will pick up charge q and accelerate in the electric field toward the opposite electrode. Upon contact with this second electrode, the shuttle transfers charge and acquires an equal but opposite charge $-q$. The shuttle then accelerates back towards the first electrode to begin the cycle anew. In this manner, a net shuttle current of $I = 2qf$ is established, where f is the shuttle frequency.

In certain nanoscopic systems, the overall charge transport mechanism may involve a combination of charge shuttling and single-electron charging physics [2]. In the present paper, we show that a *macroscopic* charge shuttle can be used to uncover fundamental aspects of the shuttling process alone, without additional transport complexities. We find that the interaction of shuttle motion with other "motional modes" of the system influences the dynamics such as to produce pronounced *discontinuous jumps* and *hysteresis* in the charge transport current-voltage (I-V) characteristics. These concepts provide fundamental guidance towards the understanding of more complex shuttle structures, particularly electronic nanosystems having movable parts.

The basic charge shuttle configuration is one having a long history dating back to the high-voltage "electrostatic bell" experiments performed by Gordon, Franklin, and others [3]. A similar configuration is often used in conjunction with an electrostatic generator as a classroom demonstration. In comparison, the shuttle systems we discuss here are scaled down considerably in both size and operating voltage. In addition, we introduce the technique of simultaneous I-V and frequency measurements as a means of probing the detailed character of charge shuttle transport.

Ground-breaking theoretical work [1] recently suggested that charge shuttling may be responsible for the unusual jumps and hysteresis in the I-V transport characteristics of silver-coated DNA stretched between two electrodes [4]. To explain these features, it was proposed that silver metal grains on the DNA backbone may mechanically oscillate between the electrodes in a "mass-on-spring" fashion and shuttle charge across the device. Extending these ideas, we find that, in general, a restoring spring force is not a necessary requirement for sustained shuttle motion, but rather that a simple motional constraint is often sufficient. Charge shuttle phenomena may play an important role in other types of systems, including, for example, organically coated nanoparticles [5], the "bucky shuttle" [6], suspended carbon nanotubes [7], and microelectromechanical systems [8].

To investigate the details of shuttle transport, we utilize several distinct shuttle configurations [9], but now focus on one particularly illustrative example (shown in Fig. 2). This setup consists of a spherical metal bead as the shuttle, a massive electrode, and a second electrode which is a thick flexible beam held fixed at one end. As will be discussed below, the damped harmonic oscillatory motion of the bending beam plays a key role in determining the current-voltage characteristics of this shuttle system. The shuttle is suspended by a fine filament in the form of a "V" so as to inhibit torsional motion. It should be noted that the pendulum restoring force is small and negligible

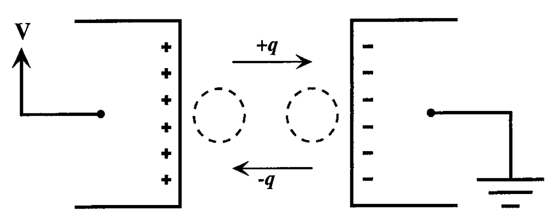

FIG. 1. Schematic of electrostatic charge shuttle motion.

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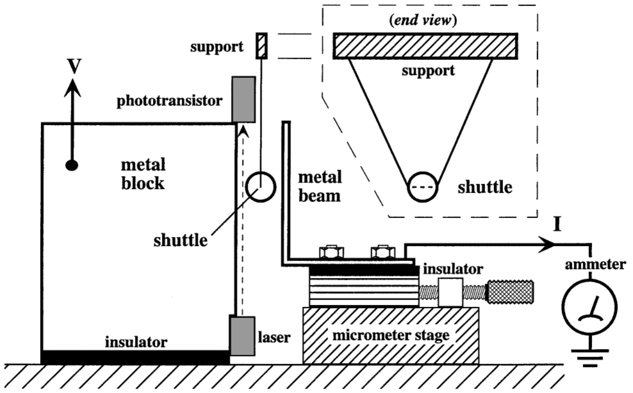

FIG. 2. Experimental setup. The block, shuttle, and beam are made of brass. The dimensions of the beam are 40 mm $\times$ 22 mm $\times$ 1.6 mm. The shuttle mass is 0.157 g, its radius 2.06 mm; the effective mass of the bending beam is 30 g, its fundamental vibrational frequency 210 Hz, and its quality factor 37. Measurements indicate the influence of another vibrational mode at 340 Hz. The micrometer is used to adjust the shuttle gap d. The natural pendulum frequency of the suspended shuttle is 2.5 Hz.

except at the lowest voltages shown here. A Keithley 610B electrometer is used for dc current measurements, and two Fluke 8842A multimeters monitor the applied dc voltage and the current amplifier output. Shuttle frequency is measured using a diode laser and phototransistor sensor in a photogate arrangement and monitored with a Tektronics TDS210 oscilloscope and frequency counter.

The basic data acquisition protocol is to measure current and frequency as a function of swept voltage (Fig. 3). Since the electrostatic force on the shuttle is a continuous function of the applied voltage, one might intuitively expect monotonic behavior for I and f. However, *discontinuous jumps* in current and *steps* in frequency are clearly observed. Furthermore, hysteresis is observed when comparing upswept and downswept traces. The frequency steps appear to ride on a background which is linear in V, whereas the trend of the current data goes as V^2.

To begin to understand the features of this data, we first consider a simple model in which the steady-state shuttle frequency is determined by the amount of inelastic energy loss associated with each shuttle-electrode collision. We make every attempt to simplify the mathematical presentation of the physics in the spirit of conveying the essential concepts of the phenomenon, and defer our detailed calculations to a longer communication [9]. We invoke a constant and "featureless" restitution factor $\beta = v_{a2}/v_{a1}$, which relates the shuttle velocity before (v_{a1}) and after (v_{a2}) a collision. The fractional loss of shuttle kinetic energy associated with each collision scales as $(1 - \beta^2)$. During a collision, the shuttle acquires a charge of magnitude $q = CV$, where C is the capacitance of the shuttle with respect to the opposite plate. After a collision, the shuttle accelerates toward the opposite electrode. For simplicity, we adopt the approximation of a position-

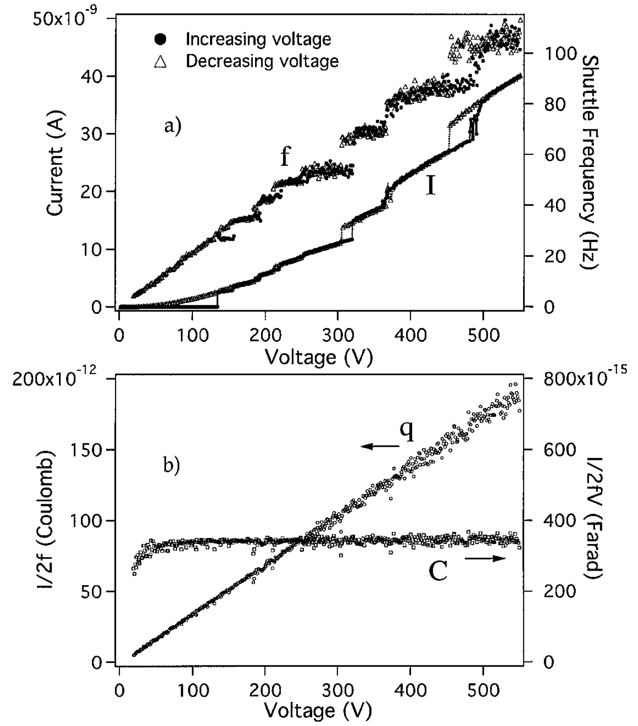

FIG. 3. (a) Current and shuttle frequency versus swept voltage for $d = 230$ μm. Hysteretic discontinuous jumps in the I-V and hysteretic stepwise behavior in the f-V are notable features. The shuttle motion, as detected optically, was observed to be quite periodic, with period fluctuations of less than 10%. (b) The charge q and capacitance C as determined experimentally from the I-f-V data.

independent acceleration $a = CV^2/md$ [10]. The steady-state shuttle frequency and shuttle current can be found using simple mechanics:

$$f = \left[\left(\frac{1+\beta}{1-\beta}\right)\frac{C}{8md^2}\right]^{1/2} V$$
$$I = 2qf = \left[\left(\frac{1+\beta}{1-\beta}\right)\frac{C^3}{2md^2}\right]^{1/2} V^2, \qquad (1)$$

where the gap d is distance the shuttle travels between collisions, and m is the mass of the shuttle. These relations do not account for jumps in the experimental data but do agree with the background voltage dependence. Since all other quantities are fixed by geometry, clearly the shortfall of such a simple model lies in the lack of frequency (or velocity) dependence in the energy transfer mechanism.

It is useful to note from Fig. 3 that the shuttle charge and capacitance—as determined from a combination of measured quantities $I/2f$ and $I/2fV$, respectively—*are* monotonic and follow the expected voltage dependencies. This verifies the expectation that $I = 2qf$ and that the capacitance is set solely by geometry.

Figure 4 shows the systematic dependence of the I-f-V characteristics on shuttle gap distance. Most pointedly, we see that, even though the voltage positions of the jumps change as the gap is varied, the positions of the

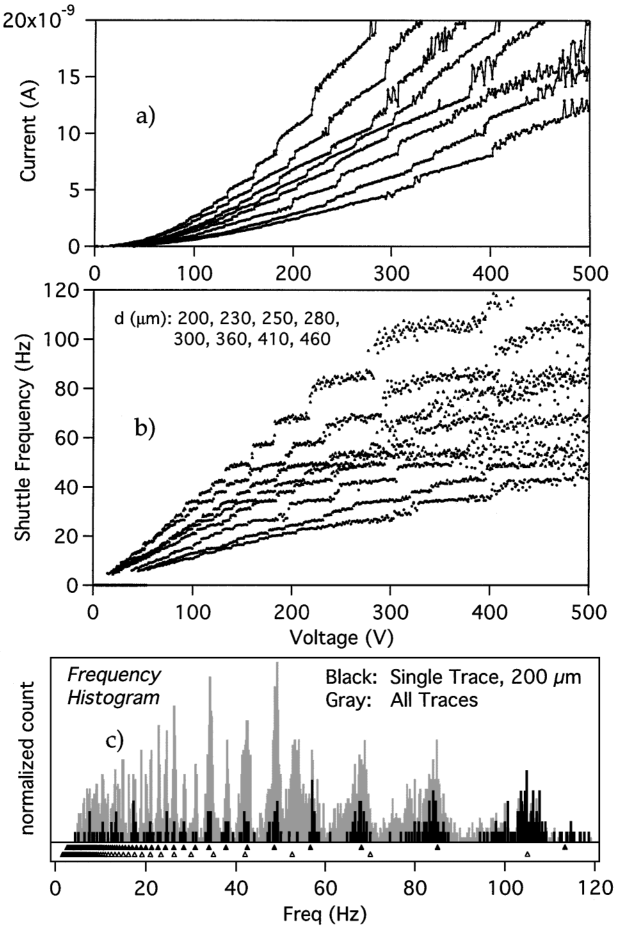

FIG. 4. (a) Current and (b) frequency traces for eight values of shuttle gap d (the smallest gap corresponds to the top curve in each case). The f-I steps move to higher voltages as the gap is increased, but occur at essentially the same values of frequency. (c) Histogram of frequency data. The open triangles mark subharmonics of 210 Hz and closed triangles mark subharmonics of 340 Hz.

steps with respect to current and frequency remain the same. A frequency histogram of this data set helps to reinforce this observation. The stepwise behavior continues down to very low frequencies ($\sim$2 Hz) as can be seen in high-resolution, low-voltage measurements. Clearly, these steps indicate the tendency to lock into special shuttle frequencies. As discussed below, this occurs when modes in the vibrational environment produce "back action" on the shuttle dynamics, so as to draw it toward favored shuttle frequencies of dynamic stability.

The frequency steps and hysteresis can be accounted for in a model which includes two dynamical parts—the shuttle and a damped harmonic oscillator (DHO) electrode—that interact each time they collide [9]. In contrast to our earlier simple model, we assume now that the shuttle loses energy only via the shuttle-beam collision which is treated as totally elastic. For a DHO with $Q \gg 1$, stable periodic shuttle motion is possible only for "states" in which the shuttle frequency is very nearly a subharmonic of the natural DHO frequency, $f = f_o/n$, where n is a positive integer. In other words, the periodic shuttle motion is forced to accommodate the fixed period of the damped harmonic oscillator. Using periodic motion as an assumption, one-dimensional equations of motion can be used recursively to predict the shuttle frequency steps analytically. In our experimental case, the mass of the shuttle is much smaller than the effective mass of the DHO, and the DHO vibrational amplitude is small compared to the shuttle gap [11].

Simple mechanics can be used to show that a sustained shuttle state of index n requires that the collision velocity of the DHO be a particular value at each collision:

$$v_{b1} = \frac{na}{2f_o}\,. \tag{2}$$

For each value of acceleration a set by the experimenter, there are several shuttle states (labeled by $n = 1, 2, \dots, n_{\max}$) which can satisfy these requirements. The allowed range of states is determined by using energy transfer considerations. During the course of a shuttle cycle, the kinetic energy of the shuttle increases by $2adm$ due to the electric field acceleration. In steady state, this amount of energy must be transferred to the DHO at each collision. It is then dissipated away by the DHO before the next collision. The rate at which energy is fed into the DHO determines its average amplitude, energy, and maximum velocity. To sustain periodic shuttle motion, it is an obvious necessity that the maximum DHO velocity exceed the required beam collision velocity of Eq. (2). This determines the range of allowed states,

$$n_{\max} = \mathrm{INT}\left[\left(\frac{8Q(mdf_o)^2}{\pi MC}\right)^{1/3}\frac{1}{V^{2/3}}\right], \tag{3}$$

where Q is the quality factor, M is the DHO effective mass, and $\mathrm{INT}(x)$ denotes the truncated integer value of x.

Within the context of this model, each allowed shuttle state is viable and locally stable. This model cannot predict, however, which of these states the system will occupy. Experimentally, we observe a general tendency towards the state of the highest allowable n (which is the lowest energy state). Evolution from one state to the next will depend on the initial conditions, the history of the experimental control parameters (e.g., voltage), and random fluctuations caused by ambient vibrations. Equation (3) shows that $n_{\max}$ is reduced in a stepwise fashion as the voltage V is increased. Using an assumption that the system occupy the $n_{\max}$ state as V is increased, the frequency $f = f_o/n_{\max}$ and current $I = 2CVf_o/n_{\max}$ are predicted to change in a stepwise fashion upon increasing voltage (Fig. 5), in general agreement with experiment. The multistate character of this model predicts hysteretic behavior, but it does not provide the means for quantitative comparison with the degree of experimental hysteresis.

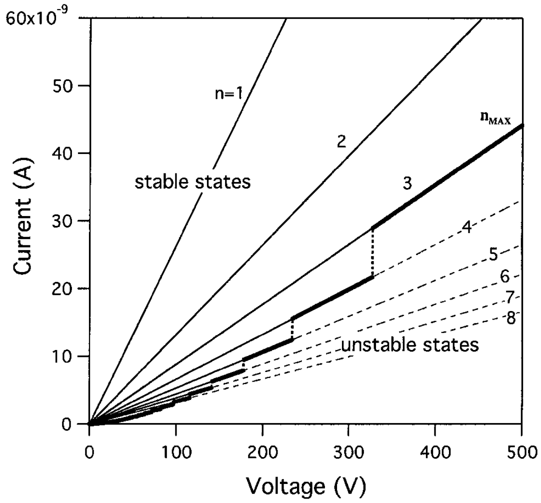

FIG. 5. Theoretical I-V curves for different shuttle frequency states. The dark curve shows the I-V curve corresponding to the lowest allowed shuttle frequency for increasing voltage. (Parameters for the vibrational mode at 340 Hz are used in this representation, with $d = 200$ μm and $C = 0.39$ pF determined experimentally and $Q/M = 9.2 \times 10^3$ kg^{-1} used as a fitting parameter.)

In our experiment, the histogram of Fig. 4 suggests the influence of *two* vibrational modes (210 and 340 Hz) in the shuttle environment. Quantitative comparison with the experimental I-V curves is met by incorporating both of these two modes into the model. To generalize these ideas, the charge transport characteristics of a shuttle with a more complex vibrational environment will be reflective of the density of vibrational modes of that particular system.

In conclusion, a macroscopic charge shuttle interacting with a simple vibrational environment is seen to possess interesting multistate dynamics. These result in discontinuous jumps and hysteresis in the charge transport characteristics. This model system serves as a general guide in understanding the current-voltage properties of micro- and nanoelectronic systems as they interact with their local vibrational environments.

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[10] The acceleration is actually position dependent as the shuttle traverses the gap. None of the essential features are lost in making the approximation of a constant average acceleration.

[11] We observe a crossover into chaotic, nonperiodic motion when using DHO beams of high Q.