A digitally configurable measurement platform using audio cards for high-resolution electronic transport studies

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We report on a software-defined digitally configurable measurement platform for determining electronic transport properties in nanostructures with small readout signals. By using a high-resolution audio analog-to-digital/digital-to-analog converter in a digitally compensated bridge configuration we significantly increase the measurement speed compared to established techniques and simultaneously acquire large and small signal characteristics. We characterize the performance (16 bit resolution, 100 dB dynamic range at 192 kS/s) and demonstrate the application of this measurement platform for studying the transport properties of spin-valve nanopillars, a two-terminal device that exhibits giant magnetoresistance and whose resistance can be switched between two levels by applied magnetic fields and by currents applied by the audio card. The high resolution and fast sampling capability permits rapid acquisition of deep statistics on the switching of a spin-valve nanopillar and reduces the time to acquire the basic properties of the device – a state-diagram showing the magnetic configurations as function of applied current and magnetic field – by orders of magnitude. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4709498]

I. INTRODUCTION

Studies of the electronic transport properties of devices and materials require specialized instrumentation. Most transport studies break down into two classes: current-voltage (I-V) characterization and differential resistance measurements. Differential resistance is typically measured using a lock-in amplifier. A lock-in amplifier is a robust solution for accurate low-noise measurements of the voltage response $\delta V$ to a small excitation current, $\delta I$. This type of measurement has a narrow noise bandwidth and can be conducted above the $1/f$ noise threshold with high dynamic reserve. However, directly measuring the current-voltage characteristics for magnetic nanostructures is a challenging task as the signals are very small compared to the quantization of a digital synthesizer used to generate the stimulus.

A new solution for simultaneous measurements of complex signals, including differential measurements and I-V characteristics, is presented using high-resolution audio analog-to-digital/digital-to-analog converters as a software-defined digitally reconfigurable measurement platform. Audio cards are versatile instruments, with 24-bit processing and functionality as a signal generator with less than $-100$ dBc harmonic distortion. Audio cards also can be configured as a narrow bandwidth ac voltmeter, with better than 110 dB dynamic range. With such high resolution, these devices outpace many direct digital synthesizers as a pure sine-wave generator and rank with commercial lock-in amplifiers in dynamic rejection. Audio cards also have multiple synchronized inputs and outputs which permit simultaneous characterization of multiple devices. Furthermore, some audio cards come with optical isolation and can be configured to be battery operated to eliminate potential group loops.

II. AUDIO CARDS

We present the configuration of an USB-based audio card – the E-MU 0404 (Creative Professional) – for static and dynamic transport measurements, which can be assembled very economically compared to commercial scientific instruments. This measurement device permits sourcing and detecting differential signals $\delta V/\delta I$ as well as sensing I-V characteristics simultaneously. We then present measurements of magnetic nanostructures, whose current-voltage and differential resistance are used to determine their underlying magnetic and electronic properties.

Our measurement setup is centered around a single audio card connected via USB to a PC. The audio card possesses two balanced high-impedance (1 M$\Omega$) inputs and two unbalanced analog outputs ($V_{pk} = 2$ V). Analog-to-digital (A/D) and digital-to-analog (D/A) conversion is done with internal sampling rates (44.1, 48, 88.2, 96, 176.4, and 192 kS/s) and 24-bit input/output (I/O) processing. Also included are optical digital interconnects (S/PDIF) for synchronous I/O over multiple audio cards. The data are read from the audio card using the Steinberg Audio Stream Input/Output (ASIO SDK) drivers, which are controlled using a Python wrapper (PyAudio) around PortAudio C programming libraries.

A. Spectral characteristics

We have tested some standard spectral characteristics of the audio card, many of which are described in standard electronics texts. Figure 1 demonstrates the noise figure, a measure of the noise added by the A/D converter at the input stage to the thermal noise inherent in a load resistor. For a variety of input resistances, the noise figure generated from a fast fourier
transform (FFT) of the input noise (bandwidth Δf = 0.2 Hz) referenced to the Johnson-Nyquist noise is nearly flat across the frequency spectrum (20 Hz–20 kHz). The noise figure approaches the Johnson noise for larger impedances, which suggests that voltage noise at the input stage plays a role for the smaller load impedances. Furthermore, the input noise is only one order of magnitude larger than the best input noise for a commercial lock-in amplifier.\(^6\) Figure 2 illustrates the spectral purity of the entire audio card by connecting the output of the D/A converter (a sine wave at 6 dB below full scale) into the A/D converter without preamplification. The calculated ratio of signal to noise and distortion (SINAD) from a FFT of the input signal leads directly to the effective number of bits (ENOB), which is a measure of the quality of the I/O digitization. A nearly constant value of 16 bits indicates that of the full 24 bits resolution, the upper 16 bits contain useful information above the noise floor, which is critical for sensing small signal changes over a larger background signal. Other useful spectral properties of the measured output include total harmonic distortion plus noise (−99.5 dBc (decibels below carrier)), signal-to-noise (−100.5 dBc), spurious free dynamic range (−112 dBc), and the noise floor (−132 dBc). Thus, we have an I/O device that functions as an ultra-low distortion, 24-bit resolution signal generator with an A/D input stage that measures low and higher impedance devices alike with relatively flat noise density over the range of audible frequencies.

**B. Measurement circuits**

Figure 3 illustrates the configuration we use for transport measurements. The top-left block represents the USB-based audio card, whose two outputs, L and R, are amplified and fed into two 1 kΩ resistors (chosen to be two orders of magnitude larger than the sample resistance) to create two stiff current sources, which feed into the sample (Z\(S\)) and a potentiometer (Z\(P\)). Leads across the terminals of Z\(S\) feed into the V\(_S\) audio card input and permit direct measurement of the sample I-V characteristic and/or differential resistance.

We also implement a digitally compensated bridge measurement using the audio card. Balancing bridge designs based upon active compensation have been well established for systems where the versatility to compensate for arbitrary reactances in complex networks where capacitances and inductances need to be compensated, or even for systems where small nonlinear deviations in I-V characteristics require versatile and precise balancing.\(^7\)–\(^9\) By outputting an appropriate signal on channel L, any parasitics or reactances of Z\(S\) can be compensated for. It also functions as a high-resolution impedance meter across a wide frequency band (20 Hz–20 kHz). In addition to linear circuit impedances, we can configure this digital bridge to compensate nonlinear elements. For example, we use this type of compensation in systems where Joule heating causes a rise of a few percent in the baseline impedance of a device, more than two orders of magnitude larger than the magnetic signal.
III. EXPERIMENTS ON SPIN VALVE NANOPILLARS

Audio card measurements are especially useful for fast characterization of spin-valve nanopillars—a two terminal magnetic device composed of two uniaxial ferromagnetic layers that exhibit two stable resistance states depending on the relative magnetization orientation of the layers (see the inset of Figure 4). The spin-valve state can be toggled between high (antiparallel) and low (parallel) resistance by applied magnetic fields (field-induced magnetization switching) or by electrical currents (current-induced magnetization switching). We can determine the relative orientation of the layers by measuring the device resistance (static or differential) as a function of the applied magnetic field. However, the resistance change is small in comparison to the device resistance and the Joule heating-related nonlinearity, which requires that we measure small changes in resistance and differential resistance in order to observe the device switch between high- and low-resistance states.

A. Differential resistance

Measuring the differential resistance versus field of a spin-valve nanopillar allows us to demonstrate the use of the audio card as a lock-in amplifier. We used the audio card to source a 882 Hz excitation current (200 μA rms amplitude) to our device while simultaneously using the audio card to measure the generated voltage. We then multiplied the digitized voltage by a unit amplitude sine and cosine of the same frequency to get the in-phase and in-quadrature components of our signal in relation to our reference and use a digital, first-order Butterworth low-pass filter (time constant 30 ms) to eliminate noise and the 2f component, and then calculate the magnitude and phase from the in-phase and in-quadrature components, plotting δV/δI as a function of applied magnetic field in Figure 4.10 Sharp changes in the differential resistance indicate toggling between parallel and antiparallel magnetic orientations of the two ferromagnetic layers.

B. Magnetic state diagram

There is an interplay between applied magnetic fields and electric currents in the orientation of the two magnetic layers, which has been examined previously and is quite important for applications like magnetic random access memory.11,12 This relationship is usually plotted in the form of a state diagram, which maps out under a given applied magnetic field and direct current the boundary of different microscopic magnetization configurations of the two spin-valve layers as determined by sharp changes in measured giant magnetoresistance (GMR).

Thus far, studies of the spin-valve state diagram have been limited by the speed of the measurement, which can take several days if one wants to explore a wide parameter space of applied magnetic fields and electric currents with good field and current resolution. This is a basic characterization that has to be done before more advanced studies because it gives information about the possible states of the magnet.13-15 However, there are extensions of the state diagram measurement that have not been investigated likely due to the long measurement time. We present a new capability to quickly map out the field-current parameter space of a spin-valve nanopillar with the use of the audio card in the direct measurement (I-V) configuration.

In Figure 5, our experimental results are displayed. We measure the voltage generated across the sample, ZS, on channel “V5”, under a linear current ramp in the form of a 441 Hz triangle wave with peak amplitude Ipk = 20 mA flowing through a spin-valve nanopillar device whose cross sectional

![FIG. 4](image1.png)

**FIG. 4.** Lock-in amplifier measurement. A small ac excitation current (frequency = 882 Hz) is injected into a 300 × 50 nm² spin-valve nanopillar to probe δV/δI. The digitized voltage across the device is processed using a digital lock-in detection method with more than 110 dB dynamic range. The differential resistance is plotted as a function of measured field. Sharp changes in δV/δI indicate toggling between parallel and antiparallel magnetic orientations of the two ferromagnetic layers. (Inset) Schematic of a spin-valve nanopillar device attached to a voltage supply. Two ferromagnetic layers (blue) separated by a copper spacer (yellow) exhibit a high-resistance state when their magnetizations are antiparallel and a low-resistance state when their magnetizations are parallel.

![FIG. 5](image2.png)

**FIG. 5.** Magnetic measurements setup. (a) A 20 mA peak amplitude triangle wave flows through a spin-valve nanopillar device. The voltage measurement is conducted across the spin-valve terminals. (b) Giant magnetoresistance hysteresis loop as a function of applied current showing sharp resistance changes between parallel (P) and antiparallel (AP) orientations of the two ferromagnetic layers. (c) (H,L) state diagram showing interplay between applied magnetic fields and electric currents in stable magnetic orientations of a spin-valve nanopillar.
area is $300 \times 50 \text{ nm}^2$. The physical properties of this device have been described in detail in Ref. 16. In Figure 5(a) the voltage across the nanopillar is measured by the analog-to-digital converter (A/D) simultaneous to the application of the triangle wave from the audio card’s digital-to-analog (D/A) converter). Figure 5(b) demonstrates the corresponding GMR effect for current switching off the spin-valve from an antiparallel (high-resistance) to parallel (low-resistance) configuration and back again.

In order to map out the state diagram, we generate a triangle field ramp from our electromagnet with period $T = 8$ s and $H_{op} = 200$ mT on top of our continuous ac current. Over one half-period of the field cycle we can generate several hundred GMR curves like the one shown in Figure 5(b), and by monitoring the currents and fields at which the device resistance toggles between high and low, we arrive at the state diagram in Figure 5(c). This diagram illustrates the outer regions in which the spin-valve device is always oriented P or AP, and where the device exhibits bistability or hysteresis in the inner regions of the parameter (H, I) space. The four-second acquisition time for a magnetic state diagram is orders of magnitude faster than the duration of the conventional acquisition method.

IV. CONCLUSIONS

We have demonstrated a digitally reconfigurable measurement platform based on audio cards for high quality measurements of nanostructures. We believe that this can afford researchers great flexibility for signal processing, multiple channels for parallel studies, high dynamic range, and most importantly, high speed capabilities for deep statistical studies. We have shown the spectral properties that make high-resolution audio cards competitive with commercial laboratory instruments. The audio card unit is versatile – it can function as a tool for direct measurement of devices or it can be integrated into a digitally compensating bridge. While we have demonstrated the use of a software-defined, digitally configurable measurement platform for the study of low-impedance spin-valve devices, it should be noted that this measurement technique can be used for many types of measurements where a high quality signal source is required.

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1There are many commercially available Sound Cards. This study used the Creative Professional E-MU 0404-USB, Creative USA, see http://us.creative.com/; see http://www.focusrite.com/ for the Focusrite Scarlett line by Focusrite USA; the Roland Quad-Capture USB by Roland USA, see http://www.rolandus.com/.

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