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ABSTRACT

Rectification is an important stage in electronic circuits for any wireless radio frequency power transfer application. Currently, Schottky diodes are widely used as rectifiers; however, they are inefficient at low power levels of microwatts or less (providing maximum sensitivities around 4 mV/μW). Nanoscale magnetic tunnel junctions can serve as alternative rectifiers by utilizing the so-called spin-torque diode effect, demonstrating a much higher rectification sensitivity (200 mV/μW) compared to Schottky diodes. However, for this mechanism to work, the signal frequency must match the ferromagnetic resonance frequency, which typically lies in the gigahertz range. For signals in the megahertz range or lower, Schottky diodes remain the only option for rectification. Here, we demonstrate a mechanism based on thermally activated adiabatic stochastic resonance in magnetic tunnel junctions to produce low frequency (up to tens of megahertz) signal rectification at low input power (submicrowatt), with a sensitivity of up to 35 mV/μW—higher than state-of-the-art Schottky diode rectifiers at this frequency and power range. These findings suggest magnetic tunnel junctions as potential alternatives to Schottky diodes for low frequency and low power applications.

In applications involving the transmission of electric energy without wires, rectifiers play a key role in extracting enough direct current from the incident electromagnetic radiation to power simple devices.[1–3] Typically, rectifier circuits are based on nonlinear impedance components, such as Schottky diodes.[4] Devices operating at radio frequency power higher than 10 mW are the only ones that can reach more than 80% rectification efficiency.[4] However, for applications such as bionic implants[5–8] or nanoscale sensors of weak low frequency signals that involve low power levels of several microwatts or less, Schottky devices exhibit low sensitivity (typically up to ~4 mV/μW)[9] that reduces the rectification efficiency to values below 1% at submicrowatt levels.[4]

Nanoscale magnetic tunnel junctions (MTJs) provide an alternate approach to achieve signal rectification of low power signals. Nanoscale MTJs are composed of two ferromagnetic layers, called the reference and free layers, which are separated by an insulating layer. These devices can serve as current-controlled microwave nano-oscillators by converting direct current to microwave voltage oscillations through tunneling magnetoresistance.[10–14] Alternatively, they can perform frequency rectification of voltage oscillations using the spin-torque diode effect,[15] also known as spin-torque-induced ferromagnetic resonance.[16] Currently, the highest reported MTJ rectification sensitivity is ~200 mV/μW, made possible based on the injection locking mechanism.[17] To achieve this rectification sensitivity, the radio frequency signal to be rectified must be applied to the device at a frequency that is close to the ferromagnetic resonance frequency of the MTJ free layer. This method limits the working frequency range to several gigahertz. However, a recent study demonstrated broadband MTJ rectification in a frequency range from 100 MHz to 500 MHz.[18]

To achieve such broadband rectification, the input radio frequency power must be sufficiently high (>0.5 μW), and so the free magnetic layer oscillation of the MTJ becomes a large-amplitude magnetization precession nearly independent of the input frequency.[18] However, for low power (<0.5 μW) signal rectification at low frequencies (from 0 to 100 MHz), there is currently no alternative to Schottky diodes.

In this work, we demonstrate an MTJ that displays low frequency signal rectification by thermally activated adiabatic stochastic resonance. At zero bias, the nanoscale MTJ features two stable magnetic states of the free layer—parallel and antiparallel to the reference layer magnetization. The stability of these states is defined by the shape anisotropy of the MTJ free layer.[19] Due to the tunnel magnetoresistance effect, each state presents different electrical resistances, with low resistance when the magnetizations of the two layers are parallel and high resistance when the magnetizations are antiparallel. It is well established that thermal fluctuation can induce switching between the two stable states.[20] An electric current or external magnetic field can modify the amplitude of the thermal fluctuations of the magnetization and thereby control the transition rates as the magnetization of the free layer is thermally switched.[21–23] Because of the exponential sensitivity of the transition rates to the current,[21–23] a small alternating current can induce transitions between both states at the driving period. This phenomenon is known as adiabatic (low-frequency) stochastic resonance.[24] Through this mechanism, we show broadband rectification of the alternating radio frequency signal at a low frequency of up to several tens of megahertz and at an input power ranging from nanowatts to a hundred microwatts. By injecting low frequency alternating current into the device, we show that it can generate a rectified output voltage with a rectification sensitivity of up to 35 mV/μW surpassing the state of the art Schottky diode limitations.

We employed an elliptical cross-sectional MTJ nanopillar (see the supplementary material for a detailed description of MTJ fabrication and composition). To demonstrate low frequency signal rectification, we operated the device with a radio frequency input signal. The supplementary material shows a detailed description of the experimental setup [Fig. S1(c)]. We applied a radio frequency input of 0.1 MHz and then swept the input power of the radio frequency signal from 0.01 μW to 100 μW. From the input power, we calculated the radio frequency power dissipated in the device, taking into account the reflection coefficient[4,25] between the device and the signal generator. The electrical model to calculate the reflection coefficient[4,25] takes into account interfacial capacitance, interfacial resistance, junction inductance, series resistance, and junction capacitance. However, the reactive elements (inductance and capacitances) give negligible contributions to the device impedance compared to the MTJ junction resistance in the low frequency regime employed in this work. Then, to calculate the reflection coefficient, we assumed that the MTJ resistance was 2400 Ω, which is the mean resistance between the parallel and antiparallel resistances [see supplementary material Fig. S2(a)]. Figure 1(a) shows the measured rectified voltage at the output of the device as a function of the dissipated radio frequency power as we applied different external magnetic fields along the in-plane long axis of the elliptical nanopillar. We observed the highest rectified voltage when the external magnetic field was 16 mT, which is the smallest magnetic field at which hysteretic behavior of resistance vs field disappears [see supplementary material Fig. S2(a)]. When the magnetic field is less than 16 mT, the MTJ is in the hysteresis regime and therefore

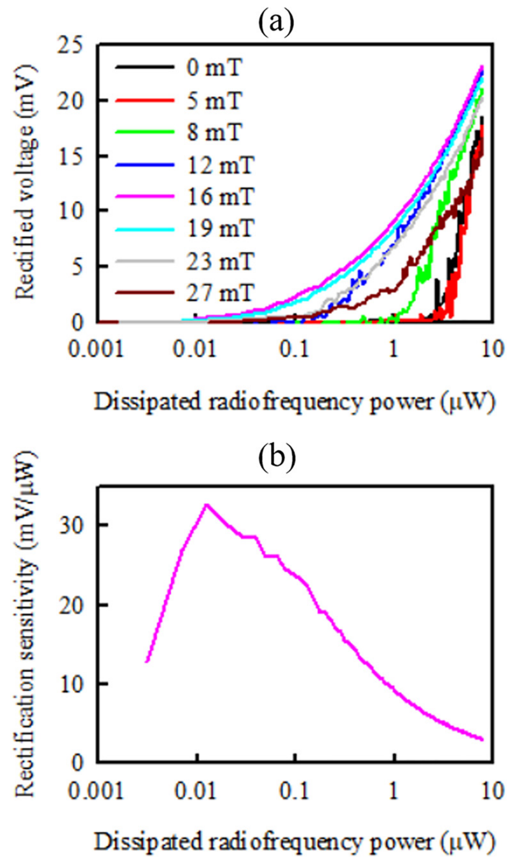

FIG. 1. (a) Rectified voltage for different external magnetic fields. (b) Rectification sensitivity at 16 mT. The input signal frequency is 0.1 MHz.

the input power to the MTJ has to overcome a high threshold value to produce a rectified voltage, as we observed in Fig. 1(a). For magnetic fields exceeding 16 mT, we observed a smaller rectified voltage [see supplementary material Fig. S2(a)] because the magnetic energy barrier between the two stable states decreases and random thermal switching between the two stable states of magnetization dominates the dynamics.[22]

Figure 1(b) shows the rectification sensitivity at 16 mT, calculated as the ratio between the rectified voltage and the dissipated radio frequency power at 0.1 MHz. The MTJ rectification sensitivity starts to exceed the noise floor once the power surpasses a threshold of 3 nW and reaches a maximum sensitivity of 32.8 mV/μW at a power of 12 nW. At higher power, the sensitivity starts to decrease. The rectification sensitivity provides a rectification efficiency of 3.5%. This is higher than the state of the art Schottky diode, which falls well below 1% at submicrowatt input power levels.[4]

Adiabatic stochastic resonance induced by spin torque[24] explains our results in Figs. 1(a) and 1(b). Thermal fluctuations can induce switching between the two stable states. Spin torque is known to amplify the amplitude of the thermal fluctuations in one of the potential wells of uniaxial magnetic anisotropy of the free layer and suppress them in the other well, which induces switching from the first well to the second.[20] The electric current and the external magnetic field modify the amplitude of the thermal fluctuation of the magnetization, which affects the transitions rates of the thermally activated switching of the free layer. The transition rates of a thermally activated switch between high resistance and low resistance can be described by the Kramers equation,[21–23]

$$\tau = \tau_0 \exp\left(\frac{E_a(I,H)}{k_B T}\right), \quad (1)$$

in which τ_0 is an attempt time that depends on the bistable potential shape, T is the temperature, E_a is the effective activation barrier, I is the bias current, H is the magnetic field, and k_B is the Boltzmann constant. The Kramers transition rates between the parallel to antiparallel states and vice versa can be modulated by the magnetic field and the applied bias current. For a magnetic field value making the double-well magnetic potential symmetric, the transition rates are equal for both transitions, from parallel to antiparallel and vice versa. The application of an alternating current in addition to the bias magnetic field induces spin torque and modulates the transition rates with the signal period. Then, the excitation by a small alternating current induces periodic modulation of the transition rate, which is exponentially sensitive to the current, and thereby induces quasiperiodic transitions between both states at the driving frequency. When the transition rates between the two states are equal, the quasiperiodic transitions produce quasiperiodic switching in the resistance of the device, which, combined with the alternating current, produce a highly efficient signal rectification. In the regime of low radio frequency power, increasing alternating current drive leads to an exponential increase in the Kramers switching rate, as expected for stochastic resonance. We thus expect an exponential increase in the rectified voltage in the alternating current drive amplitude. Since the sensitivity is defined as rectified voltage divided by the applied power (quadratic in the ac drive), the sensitivity increases with increasing radio frequency power. For sufficiently high radio frequency drive, the switching rate becomes nearly equal to the drive frequency and thus the switching rate saturates. In this regime, rectified voltage becomes a linear function of the alternating current drive. Therefore, in the regime of high radio frequency power, the sensitivity is expected to be approximately inversely proportional to the applied alternating current (inversely proportional to the square root of the applied radio frequency power). These expectations are consistent with the data in Fig. 1(b). It is important to note that temperature alone cannot be responsible for rectification. Temperature cannot induce synchronization of the transitions between the parallel and antiparallel states to alternating current. It can increase the rate of transitions, but they will be random and will not lead to a rectified voltage.

The average amplitude of the oscillations by adiabatic stochastic resonance decreases with increasing drive current frequency. A precipitous drop of the resonance amplitude is expected for an alternating current frequency exceeding the Kramers transition rate.[23,24] In this case, the magnetization of the free layer does not have sufficient time to switch via the thermally activated process during the half-period of the alternating current. At frequencies significantly exceeding the transition rate, the rectification sensitivity due to stochastic resonance approaches zero. At very high frequencies, rectification due to ferromagnetic resonance takes place when the drive frequency is near a spin wave resonance frequency of the system.[15]

To verify that the rectification sensitivity decreases with increasing frequency, we studied the dependence of the rectified voltage with the input signal frequency. Figure 2(a) shows the rectified voltage vs the input power obtained at different frequencies ranging from 0.1 MHz to 100 MHz. We note that the threshold radio frequency power necessary to produce a rectified voltage increases with frequency, specifically from 3 nW to 8 μW when the frequency increases from 0.1 MHz to 10 MHz, respectively. Figure 2(a) also shows that for a given

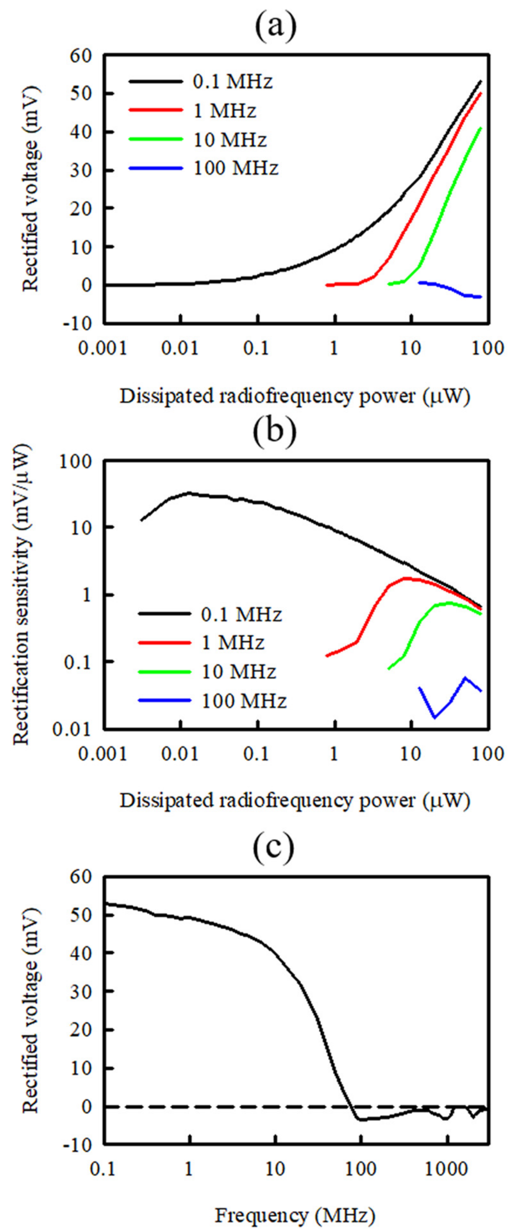

FIG. 2. (a) The rectified voltage and (b) efficiency as a function of the radio frequency dissipated power for different input frequencies. (c) Rectified voltage for a radio frequency power of 80 μW vs frequency.

input power, the rectified voltage decreases with increasing frequency from 0.1 MHz to 10 MHz. This result demonstrates that the MTJ works as a broadband frequency rectifier, which is a characteristic of thermally activated adiabatic stochastic resonance.[24] If the signal frequency exceeds the Kramers transition rate, the switching probability in a half-period of the radio frequency current oscillation becomes small. Thus, the amplitude of the rectified voltage decreases with increasing frequency[23] and the rectification becomes less efficient. Because the Kramers transition rate is on the microsecond time scale for the small MTJs studied in this work,[26] rectification due to adiabatic stochastic resonance should be limited to frequencies up to several megahertz. Figure 2(a) also shows that for a frequency of 100 MHz, the rectified voltage is negative. This suggests that the rectified voltage at 100 MHz is due to the ferromagnetic resonance mechanism.[15] In Fig. 2(a), we also note that the rectified voltage is 53 mV for an input power of 80 μW at 0.1 MHz. This voltage is much higher than rectified voltages obtained by means of ferromagnetic resonance, which typically is limited to rectified voltages of 5 mV due to dielectric breakdown of the MgO barrier.[27] The maximum radio frequency power that we applied to the device was 80 μW. Taking into account this power and the MTJ resistance of 2400 Ω, the maximum amplitude of the applied RF current was 260 μA. The critical current of the junction for our devices has been previously estimated to be approximately 1.5×10^7 A/cm^2.[28,29] Given the lateral dimensions of our MTJ [see Fig. S1(b) of the supplementary material], the critical current is then approximately 0.6 mA. This value is significantly larger than the maximum drive current employed in our measurements, which proves the thermally activated character of the free layer switching needed for stochastic resonance.

Figure 2(b) shows the rectification sensitivity corresponding to the rectified voltage in Fig. 2(a). The rectification sensitivity clearly shows that there is an input power threshold that increases with frequency. It also shows that the sensitivity decreases with increasing frequency. This finding verifies that adiabatic stochastic resonance is responsible for the rectification.

To verify that the observed negative rectified voltage is from the mixing between the input signals with a ferromagnetic resonance mode of the MTJ, we measured the rectified voltage in a frequency range from 0.1 MHz to 3 GHz. The rectified voltage should have voltage peaks at the same frequencies as the ferromagnetic resonance modes shown in Fig. S2(b) of the supplementary material. Figure 2(c) shows the rectified voltage at different input signal frequencies for a radio frequency power of 80 μW. We observe that at low frequency, the rectified voltage is positive, as expected from adiabatic stochastic resonance. However, the rectified voltage decreases as frequency increases, and as a consequence, the rectification efficiency also decreases in accordance with Fig. 2(b). At a frequency of 75 MHz, the rectified voltage flips from positive to negative voltage. For frequencies higher than 75 MHz, we observed three peaks of negative rectified voltage at frequencies of 100 MHz, 900 MHz, and 2 GHz. We note that the peaks at 900 MHz and 2 GHz are close to the ferromagnetic resonance (spin wave resonance) peaks observed in the power spectrum of the MTJ in Fig. S2(b) of the supplementary material (870 MHz and 1.85 GHz). Different factors can explain the frequency shift that we observe between the frequencies of the rectified voltage peaks and the spin wave resonance peaks. First, the spin-torque effect in the MTJ produces resistance oscillations with frequencies that shift with the input current amplitude.[30] Taking this into account, we cannot assume the oscillation frequencies in Fig. S2(b) of the supplementary material, which we obtained using a direct current of 100 μA, as precise eigenfrequencies. Additionally, different heating mechanisms when exciting with direct and radio frequency currents can produce resistance oscillations at different frequencies.[22] The peak at 100 MHz is likely to be of nonmagnetic origin because this frequency is too low to be associated with a spin wave resonance.

In this work, we have demonstrated an MTJ that can act as a broadband signal rectifier with an upper cutoff frequency of 75 MHz. The device rectifies the radio frequency signal by mixing it with the quasiperiodic resistance oscillations between the parallel and antiparallel states of the device (due to adiabatic stochastic resonance induced by spin torque). The rectification sensitivity is on the order of several millivolts per microwatt and increases significantly to up to tens of millivolts per microwatt at frequencies lower than 1 MHz. The power threshold increases with frequency until the rectification disappears at 75 MHz. The rectification is limited in frequency by the Kramers transition rate of switching from the parallel to antiparallel states. We could increase the rectification efficiency by increasing the difference between the parallel and antiparallel resistances. This can be achieved by annealing the MTJ at high temperature above 500 °C while suppressing the Ta diffusion into the CoFeBe electrodes.[31] We can also produce a higher rectified voltage by employing several MTJs connected in series to produce a cascade rectification effect. Ultimately, our results enable MTJs to work as highly efficient rectifiers at low frequencies.

See the supplementary material for details about the device fabrication and characterization as well as for extended details about the experimental setup employed to measure the rectified voltage.

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