Benchmarking of Spin–Orbit Torque Switching Efficiency in Pt Alloys

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A magnetic heterostructure with good thermal stability, large damping-like spin–orbit torque (DL-SOT), and low power consumption is crucial to realize thermally stable, fast, and efficient magnetization manipulation in SOT devices. This work systematically investigates on Pt$_{0.57}$Cu$_{0.43}$/Co/MgO magnetic heterostructures with perpendicular magnetic anisotropy (PMA), and reports a promising spin Hall material, Pt–Cu alloy, possessing large DL-SOT efficiency and moderate resistivity. The optimal Pt$_{0.57}$Cu$_{0.43}$ has a large DL-SOT efficiency of about 0.44, as determined by hysteresis loop shift measurements, with a relatively low resistivity (82.5 μΩ cm at 5 nm thickness). Moreover, this large DL-SOT efficiency and the coercivity reduction accompanying with proper alloying contribute to a low critical switching current density ($2.37 \times 10^6$ A cm$^{-2}$ in the Pt$_{0.57}$Cu$_{0.43}$ layer) in current-induced magnetization switching measurements. Finally, the thermal stability of the Co layer can be preserved under alloying, whereas the switching power consumption can be significantly reduced, being the best performance among reported Pt-based spin current sources. This systematic study on SOT switching properties suggests that Pt$_{0.57}$Cu$_{0.43}$ is an attractive spin current source with moderate resistivity, large DL-SOT efficiency, good thermal stability, and low power consumption for future SOT applications.

1. Introduction

The spin–orbit torques (SOTs) exerted by spin currents ($J_s$) on ferromagnetic (FM) layer are capable to effectively manipulate magnetization in nanoscale, such as magnetization switching\cite{1-3} magnetic domain wall motion,\cite{4,5} and magnetization dynamics at microwave or terahertz frequency.\cite{6} Among versatile applications, SOT-magnetic random-access memories (SOT-MRAM) promise merits, such as energy efficiency, fast operation speed, and therefore is an attractive candidate to replace the contemporary memory technologies. Unlike the spin-polarized $J_s$ in spin-transfer torque (STT)-MRAM, the pure spin current $J_s$ in SOT-MRAM majorly arises from bulk spin Hall effect (SHE)\cite{7,8} interfacial Rashba effect,\cite{9,10} or spin-momentum locking.\cite{11-13} The SHE is generally originated from 5d heavy metal (HM) with strong spin–orbit coupling (SOC), such as Pt,\cite{14} Ta,\cite{1} and W.\cite{15} The interfacial Rashba effect happens at the interface with strong SOC and broken inversion symmetry, such as Bi$_2$/Ag,\cite{16} α-Sn/Ag,\cite{17} and Bi$_2$Se$_3$/Ag interfaces. The spin-momentum locking stems from the topologically protective surface states of topological insulators, such as BiSe\cite{19-21} BiSb\cite{22} and (BiSb)$_2$Te$_3$.\cite{21}

For SOT-MRAM applications, the most critical figures of merit are scalability, thermal stability, and power consumption. The first two factors can be optimized by introducing FM layer with decent perpendicular magnetic anisotropy (PMA).\cite{24} Common approaches include employing HM/FM interface with strong SOC,\cite{25} orbital hybridization at the FM/oxide interface,\cite{26,27} or bulk PMA materials.\cite{28} As for power consumption, the power required for reversing a single bit per volume, excluding current shunting to the FM layer, is $p \propto \rho_{HM} J_{HM}^2$, where $\rho_{HM}$ is the longitudinal resistivity of HM, and $J_{HM}$ is the switching charge current density in the HM channel. Generally, the SOT switching is governed by the damping-like SOT (DL-SOT), and the DL-SOT efficiency ($\xi_{DL}$) is inversely proportional to the critical $J_{HM}$. Under the SHE scenario, the $\xi_{DL}$ with a perfect spin transparency ($T_{int}$) at the HM/FM interface can be written as\cite{29}

$$\xi_{DL} \equiv \left( \frac{2e}{h} \right) \sigma_{SH}^{HM} \rho_{xx}^{HM}$$

where $e$ is the elementary charge; $h$ is the reduced Plank constant; $\sigma_{SH}^{HM}$ and $\rho_{xx}^{HM}$ are spin Hall conductivity and resistivity of HM, respectively. Besides improving power consumption, lower current density can also avoid device degradation due to electromigration and then ensure the device endurance; a practical scale is below few $10^7$ A cm$^{-2}$. To reduce $J_{HM}$, a straightforward approach is to enhance $\xi_{DL}$ by using more resistive spin current source (SCS; $\beta$-W,\cite{30} $\beta$-Ta,\cite{1} BiSe,\cite{31} and BiSb\cite{22}) or raising $\rho_{xx}^{HM}$ in certain materials system (nitrogen/oxygen doping,\cite{32} crystallinity engineering,\cite{33} alloying,\cite{34-37} and thin layer insertion\cite{38,39}), based on the theoretical prediction\cite{40} that intrinsic $\sigma_{SH}^{HM}$ is independent of resistivity change. So far, the reported low $J_{HM}$ ranges between $10^6$ and $10^7$ A cm$^{-2}$. However, with raising $\rho_{xx}^{HM}$, possible side effects include the increase of power consumption per switching, energy dissipation due to

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detrimental current shunting, or poor SOT device endurance.[41] Moreover, engineering on spin Hall metal could possibly weaken the PMA of FM layer, thereby attenuating the device retention. As a result, it is crucial to find an optimized material system simultaneously possessing good PMA, large DL-SOT efficiency, and moderate resistivity for a more applicable SOT-MRAM.

In this work, we choose co-sputtered Pt–Cu alloy as the tentative SCS. Compared to other resistive spin Hall metal (W, Ta, etc.), Pt is a particularly attractive candidate for SOT device applications due to its relatively low resistivity and large intrinsic spin Hall conductivity from its band structure.[32] However, the reported $\sigma_{\text{Pt}}^{\text{DL}} = 0.07 \sim 0.12 \Omega^{-1} \text{cm}^{-1}$ is still quite low in several Pt/FM systems,[14,42] and the price concern from scarcity also makes it less attractive in mass production than Ta or W; the dopant Cu, rather than other resistive impurities used in previous works, is conductive, inexpensive, and widely adopted in modern complementary metal-oxide-semiconductor process, and thus can serve as an ideal scattering impurity. Despite several works have shown that Pt–Cu alloy have larger spin Hall angle than Pt,[43,44] a direct demonstration on its SOT switching performance has not yet been investigated. We first ensure PMA can be obtained in Pt$_x$Cu$_{1-x}$(5)/Co(1)/MgO(2) heterostructures, then determine the DL-SOT efficiency $\sigma_{\text{DL}}^{\text{Pt-Cu}}$ by hysteresis loop shift measurements. Within the PMA regime, tunable $\sigma_{\text{DL}}^{\text{Pt-Cu}}$ and coercivity are observed. The enhanced $\sigma_{\text{DL}}^{\text{Pt-Cu}}$ resulting from the raised $\rho_{xx}^{\text{Pt-Cu}}$ by optimal alloying of Pt is $\approx 0.44$ for Pt$_{0.57}$Cu$_{0.43}$, and the obtained

$$\sigma_{\text{Pt-Cu}}^{\text{DL}} \approx 5.38 \times 10^5 \Omega^{-1} \text{cm}^{-1}$$. We furthermore perform current-induced magnetization switching on heterostructures with PMA. Deterministic SOT switching is achieved, and the lowest critical switching current density in Pt$_x$Cu$_{1-x}$ layer is $\approx 2.37 \times 10^7 \text{A cm}^{-2}$ for Pt$_{0.57}$Cu$_{0.43}$. This large reduction on critical switching current is attributed to the concurrent enhancement of $\sigma_{\text{DL}}^{\text{Pt-Cu}}$ and the reduction of coercivity by alloying. Also, good thermal stability is maintained within the PMA regime, and the lowest zero-thermal critical switching current is $\approx 1.12 \times 10^7 \text{A cm}^{-2}$ for Pt$_{0.57}$Cu$_{0.43}$. The lowest power consumption without current shunting is $\approx 4.64 \times 10^{11} \text{mW cm}^{-2}$ for Pt$_{0.57}$Cu$_{0.43}$, significantly lower than that from a pure Pt control sample ($1.61 \times 10^{13} \text{mW cm}^{-2}$). We further provide a comprehensive benchmarking summary of SOT switching power consumption in various materials systems, in which we show that Pt$_{0.57}$Cu$_{0.43}$ is a tentative SCS with low power consumption, moderate resistivity, and minimal shunting effect.

2. Materials Preparation and Characterization

2.1. Sample Structures, Preparation Methods, and Characterization

As illustrated in Figure 1a, Pt$_x$Cu$_{1-x}$(5)/Co(1)/MgO(2) heterostructure is sputter-deposited onto SiO$_2$ substrate with
Ar flow of 3 mTorr at room temperature. The numbers in parenthesis represent the layer thickness in nanometers, and $x$ is the atomic percentage of Pt concentration. All the samples are capped by Ta(2), which is expected to be fully oxidized under ambient atmosphere and therefore its SOT contribution is negligible. The composition of Pt$_x$Cu$_{1-x}$ is controlled by co-sputtering pure Pt and pure Cu sources under calibrated sputtering power. The saturation magnetization of this layer is characterized by a vibrating sample magnetometer (VSM) to be 1414 emu cm$^{-3}$. For the purpose of electrical characterization, the samples are lithographically patterned into Hall bar devices (5 µm × 60 µm). The average longitudinal resistivity ($\rho_{\text{long}}$) of Pt$_x$Cu$_{1-x}$ varying with Pt concentration is then characterized via typical four-point probe resistance measurements on patterned Pt$_x$Cu$_{1-x}$ (5) devices, as shown in Figure 1b. The $\rho_{\text{long}}$ of Pt$_x$Cu$_{1-x}$ increases with more Cu concentration in Pt–Cu alloy from 27.4 µΩ cm (pure Pt) to 122.5 µΩ cm (Pt$_{0.33}$Cu$_{0.67}$), then decreases to 32.7 µΩ cm (pure Cu), showing a typical resistivity trend of well-mixed alloy that resistivity is proportional to alloy randomness. The resistivity of Co is characterized to be 26.6 µΩ cm.

2.2. PMA Window

The magnetic anisotropy properties of Pt$_x$Cu$_{1-x}$ (5)/Co(1)/MgO(2) heterostructure are characterized by anomalous Hall effect (AHE) hysteresis loops, as illustrated in Figure 1a. By reading Hall resistance ($R_{\text{H}}$) under varying out-of-plane external field ($H_{\text{z}}$) with a fixed in-plane bias current ($I = 1.9$ mA), the perpendicular/in-plane magnetization anisotropy (PMA/IMA) degree can be defined as the ratio between remnant magnetization ($M_s$) and saturated magnetization ($M_s$), which is evaluated by $R_{\text{H}}$ under zero $H_{\text{z}}$ and maximum $R_{\text{H}}$, respectively; and the coercive field ($H_{\text{c}}$) is defined as the field when normalized $R_{\text{H}}$ changes its sign. As shown in Figure 1c–d, the PMA/IMA window respectively locates in the Pt/Cu-rich regime, and the lowest threshold Pt concentration to maintain perfect PMA is about 50%. At the same time, the coercivity of Co layer reduces with increasing Cu content in the Pt–Cu alloy. Both features are consistent with the trend that alloying by Cu would weaken the overall SOC of Pt–Cu alloy.

3. Results and Discussion

3.1. Damping-Like Torque Efficiency of Pt–Cu alloy

We first determine the DL-SOT efficiency ($\xi_{\text{DL}}$) of Pt–Cu alloy by current-induced hysteresis loop-shift measurements$^{[44]}$ for Pt$_x$Cu$_{1-x}$ (5)/Co(1)/MgO(2) heterostructures with PMA, which is illustrated in Figure 2a. Based on a DL-SOT + homochiral Néel domain wall motion scenario,$^{[40]}$ the magnetization experiences a perpendicular effective field ($H_{\text{eff}}$) induced by in-plane charge current ($I_{\text{app}}$ || $\delta$), which results in a shift of the out-of-plane hysteresis loop. $\xi_{\text{DL}}$ can be estimated by $H_{\text{eff}}/I$ from linear fits to $H_{\text{eff}}$ versus $I_{\text{app}}$. Under this scenario, $\xi_{\text{DL}}$ reaches a saturated value when the external in-plane field $H_{\text{c}}$ just overcomes the Dzyaloshinskii–Moriya interaction (DMI) effective field $|H_{\text{DMI}}|$ originated from the Pt$_b$Cu$_{1-x}$/Co interface and then realigns the chiral domain wall moments, as shown in Figure 2b–d. Moreover, $\xi_{\text{DL}}$ derived from a macrospin model can be written as$^{[45,47]}

$$\xi_{\text{DL}} = \left( \frac{2}{\pi} \right) \frac{2e}{h} \mu_0 M_s w_{\text{Pt-Cu}} (1 + \frac{H_{\text{eff}}}{I})$$

(2)

where $\mu_0$ is the vacuum permeability, $M_s$ and $w_{\text{Pt-Cu}}$ are the magnetization and thickness of the Co layer, respectively. $s \equiv I_{\text{FM}}/I_{\text{SH}}$ is the current shunting parameter, $w$ and $t_{\text{Pt-Cu}}$ are the width and thickness of Pt$_x$Cu$_{1-x}$ layer, respectively. Based on the $H_{\text{eff}}/I$ results obtained from hysteresis loop-shift measurements, the relationship between $\xi_{\text{DL}}$ and $\rho_{\text{Pt-Cu}}$ is summarized in Figure 2e. The largest $\xi_{\text{DL}} \approx 0.44$ for Pt$_{0.33}$Cu$_{0.67}$ (with 82.5 µm cm) is more than two times larger than $\xi_{\text{DL}} \approx 0.14$ for pure Pt (with 27.4 µm cm). Besides the doped HM itself, the interfacial conditions such as interface roughness$^{[48]}$ and spin transparency$^{[49]}$ might also affect the performance. Despite the interface, quality might be altered during alloying, $\xi_{\text{DL}}$ varies fairly linearly with respect to Pt$_{0.33}$Cu$_{0.67}$ within the PMA regime, and the lower-bounded spin Hall conductivity ($\sigma_{\text{SH, lower}}$) is estimated to be 5.38 × 10$^{-3}$ (h/2e) $\Omega^{-1}$ m$^{-1}$, close to that of pure Pt. This linear relationship indicates the bulk intrinsic Pt property is preserved during alloying, and the influence from the interface plays a minor role in this case. It is interesting to note that the preservation on intrinsic Pt property of Pt–Cu is quite different from the case of Pt-Hf, where $\sigma_{\text{SH, lower}}$ reduced as the HF concentration goes beyond 12.5%.$^{[35]}

3.2. Current-Induced Magnetization Switching

We then perform current-induced magnetization switching measurements on the Pt$_x$Cu$_{1-x}$ (5)/Co(1)/MgO(2) heterostructures with PMA. The measurement setup is illustrated in Figure 3a. We alternatively apply in-plane longitudinal write/read current pulses $I_{\text{write}}/I_{\text{read}}$ to control/sense the magnetization by DL-SOT/AHE, with the aid of an external in-plane field along $\hat{\kappa}$ to overcome the DMI effective field. The pulse width ($t_{\text{pulse}}$) of $I_{\text{write}}$ is set as 0.05 s; $I_{\text{read}}$ is set as 0.03 mA. The switching current ($I_{\text{sw}}$) is defined as the write current at which the normalized Hall resistance ($R_{\text{H}}$) changes sign; and the saturated external field ($H_{\text{sat}}$) is defined as the applied in-plane field at which the switching current reaches its minimum ($I_c = I_{\text{sw}}$). As the results shown in Figure 3b–d, deterministic current-induced magnetization switching is demonstrated, and the reversing switching polarity with opposite external field direction is consistent with the SHE + DMI scenario.

For the control experiments (pure Pt-based device), $I_c$ is about 7.30 mA and $I_{\text{sw}}$ in Pt layer is about 2.42 × 10$^6$ A cm$^{-2}$, which are close to previously reported results.$^{[31]}$ And for Pt–Cu alloy, the lowest $I_c$ is about 0.96 mA and $I_{\text{sw}}$ in the Pt$_{0.33}$Cu$_{0.67}$ layer is about 2.37 × 10$^6$ A cm$^{-2}$ for the Pt$_{0.33}$Cu$_{0.67}$-based device. This low current density is comparable to other reported conventional and emergent SCS materials at room temperature, such as $\beta$-Ta(4)/CoFeB(1)(5.47 × 10$^6$ A cm$^{-2}$)$^{[1]}$ and BiSb(5)/MnGa(3)(1.10 × 10$^6$ A cm$^{-2}$)$^{[2]}$. The trend of $I_c$ and $H_{\text{sat}}$, as changing Pt concentration is as expected and consistent with the observed trend of $\xi_{\text{DL}}$ and $H_{\text{DMI}}$ from loop-shift measurements: the larger the $\xi_{\text{DL}}$, the lower $I_c$, and the smaller $H_{\text{DMI}}$, the smaller $H_{\text{sat}}$.
Figure 2. Damping-like torque efficiency characterization. a) Schematics of a Hall bar device for anomalous Hall hysteresis loop shift measurements, where $I_{DC}$ represents the in-plane current along $\hat{x}$. $H_x$ and $H_y$ are the applied in-plane/out-of-plane magnetic field, respectively. b) Representative hysteresis loop shift results of a Pt$_{0.57}$Cu$_{0.43}$-based device under $H_x = \pm 2000$ Oe and $I_{DC} = \pm 2.5$ mA. c) $H_y^{\text{eff}}$ as functions of $I_{DC}$ of a Pt$_{0.57}$Cu$_{0.43}$-based device under $H_x = \pm 2000$ Oe. d) $H_y^{\text{eff}}/I$ as a function of $H_x$, where $H_y^{\text{max}}/I$, $H_{\text{DMI}}$ are the saturated $H_y^{\text{eff}}/I$ and the corresponding $H_x$. e) The summary of $H_y^{\text{eff}}/I$ and $H_{\text{DMI}}$ versus Pt concentration. f) Calculated damping-like torque efficiency ($\xi_{DL}$) versus longitudinal resistivity ($\rho_{xx}$) of Pt–Cu alloy, where the slashed area corresponds to samples with PMA.
Figure 3. Current-induced magnetization switching. a) Schematic illustration of current-induced magnetization switching measurements, where \( I_{\text{write}} \) is the write current along \( \hat{x} \), \( H_x \) is the in-plane external field along \( \hat{x} \), and \( J_s \) is the spin current with spin polarization along \( \hat{y} \). b) Representative current-induced magnetization loops of a Pt\(_{0.57}\)Cu\(_{0.43}\)-based device under \( H_x = \pm 1600 \text{ Oe} \). c) Switching current \( |I_{\text{sw}}| \) versus \( |H_x| \), where the critical switching current \( I_c \) and saturation field \( H_{\text{sat}} \) are the saturated \( |I_{\text{sw}}| \) and its corresponding \( |H_x| \). d) The summary of \( I_c \) and \( H_{\text{sat}} \) with varying Pt concentration. Also note that the coercive field is reduced when the Pt content is reduced. Therefore, we attribute this significant reduction of \( J_c \) to the simultaneous enhancement of SOT efficiency and reduction of coercivity of the Co layer by proper alloying.

3.3. Thermal Stability and Power Consumption

The effect of alloying on the thermal stability of heterostructures-of-interest has been largely ignored in previous studies. Since DL-SOT switching is a thermally activated process with the write current pulse we applied, the thermal stability of the Co layer can be determined by performing switching measurements with different pulse widths. Based on a thermal-assisted model, the relationship between \( I_c \) and \( t_{\text{pulse}} \) follows[50]

\[
I_c = I_{c0} \left[ 1 - \frac{1}{\Delta} \ln \left( \frac{t_{\text{pulse}}}{\tau_0} \right) \right]
\]

where \( I_{c0} \) is the critical switching current in the absence of Joule heating; \( \Delta = U/k_B T \) is the thermal stability factor representing the energy barrier between up and down state of the FM layer with PMA; \( t_{\text{pulse}} \) is the write pulse width that ranges from 0.05 to 1 s; and \( \tau_0 \approx 1 \text{ ns} \) is the intrinsic thermal attempt time. By varying \( t_{\text{pulse}} \), the \( I_{c0} \) and \( \Delta \) with different Pt concentration can be extracted and estimated from the intercept and slope by linear fits of \( I_c \) versus \( \ln(t_{\text{pulse}}/\tau_0) \), as summarized in Figure 4a,b. We find the lowest \( |I_{c0}| \approx 3.09 \pm 0.08 \text{ mA} \) for Pt\(_{0.57}\)Cu\(_{0.43}\), and \( |I_{c0}| \approx 11.88 \pm 1.10 \text{ mA} \) for pure Pt in our control experiments. Moreover, the trend of \( I_{c0} \) is consistent with the DL-SOT efficiency of Pt–Cu alloy, which reconfirms its SHE origin. It is noteworthy that no serious thermal stability degradation is observed despite alloying, with \( \Delta = 28.85 \pm 1.15 \text{ for Pt}_{0.57}\)Cu\(_{0.43}\) and \( \Delta = 32.72 \pm 1.27 \text{ for pure Pt} \). This thermal tolerance against alloying is beneficial for data retention, and ensures the performance of the SOT device.

Next, we calculate the upper bound of write power consumption per single bit per volume without current shunting and Joule heating \( p_0 = \rho J_{\text{sat}}^2 \) and switching efficiency \( \varepsilon \equiv \Delta/I_{c0} \).
where $\rho$ and $I_{c0}$ are the resistivity and critical zero-thermal switching current density in the SCS channel; $\Delta$ and $I_{c0}$ are the thermal stability and zero-thermal critical switching current of the whole device. As summarized in Figure 4c, the lowest $p_0$ is about $4.81 \times 10^{12}$ mW cm$^{-3}$ for Pt$_{0.57}$Cu$_{0.43}$, which is reduced by almost an order from that for pure Pt ($4.25 \times 10^{13}$ mW cm$^{-3}$). This reduction on power consumption is the result of lower $I_{c0}$ and moderate resistivity of the Pt–Cu alloy. If the thermal effect is further considered, the apparent power consumption ($p = \rho J_{c0}^2$) will become even lower due to the reduced $J_c$ ($4.64 \times 10^{11}$ mW cm$^{-3}$ for Pt$_{0.57}$Cu$_{0.43}$ vs $1.60 \times 10^{13}$ mW cm$^{-3}$ for pure Pt). In addition, the largest $\epsilon = 9.33 \pm 0.14$ mA$^{-1}$ for Pt$_{0.57}$Cu$_{0.43}$ is more than three times better than $\epsilon = 2.75 \pm 0.15$ mA$^{-1}$ for pure Pt, which is due to the preserved $\Delta$ and lower $I_{c0}$.

4. Benchmarking Performance among Pt Alloys

Finally, we also compare the SOT switching power consumption using Pt–Cu alloy with other common materials systems, including Pt-based,[33,34,36–38] $\beta$-Ta,[1] $\beta$-W,[51] and chalcogenide-based[19,20,22] SCSs. Note that we only focus on studies with room-temperature switching results. Given that rare works studied on $J_{c0}$, we estimate power consumption by the apparent $p = \rho J_{c0}^2$. If we further consider the energy dissipation factor ($\eta$, unitless) due to current shunting effect, the actual power consumption should be proportional to $(1 + \eta)$ with

$$1 + \eta = (1 + s) \frac{I_{SCS}}{I_{FM} + I_{SCS}},$$

where $s \equiv I_{FM}/I_{SCS} = \frac{I_{FM}}{I_{SCS}} \frac{\rho_{SCS}}{\rho_{FM}}$ is the shunting parameter, and $t$ and $\rho$ are thickness and resistivity, respectively (see Supporting Information for detailed derivations). Replacing FM to magnetic insulator is viable to achieve negligible energy dissipation from avoiding current shunting through FM layer.[52,53] But here we estimate $\eta$ based on CoFeB, a much more common FM for industrial purpose, with a specific heterostructure (SCS(5)/CoFeB(1)) with $\rho_{CoFeB} = 190 \mu\Omega$ cm). The calculated power consumption and $\eta$ are summarized in Figure 5. It is noteworthy that despite low power consumption can be achieved due to the large DL-SOT efficiency of chalcogenide-based SCSs, the enhanced energy dissipation due to current shunting from the large resistivity of SCSs actually would make it energetically
unfavorable. On the other hand, despite Pt-based SCs would not suffer from serious energy dissipation due to relatively low resistivity, the raised resistivities accompanying with alloying or thin layer insertion might compensate the merits from lower critical switching currents, even make it worse in several cases. However, Pt$_{0.57}$Cu$_{0.43}$ in this work not only significantly improves the power consumption of pure Pt (even the best among reported Pt-based SCs), but also is competitive to other SCs. With low power consumption and moderate resistivity, Pt$_{0.57}$Cu$_{0.43}$, therefore, is competitive candidate as SCS in future SOT-MRAM.

5. Conclusion

To summarize, we systematically investigate on Pt$_{1-x}$Cu$_x$/Co/MgO heterostructure with PMA. Large enhancement on DL-SOT efficiency of Pt–Cu alloy is demonstrated by hysteresis loop shift measurements, resulting from tuning resistivity by proper alloying on intrinsic Pt. The largest DL-SOT efficiency is up to 0.44 for Pt$_{0.57}$Cu$_{0.43}$ when the resistivity is raised from 27.4 to 82.5 $\mu\Omega\cdot$cm. And the lower-bound of the spin Hall conductivity of Pt–Cu alloy is about $5.38 \times 10^3$ A/(m$\cdot$T). The lowest DL-SOT efficiency is then confirmed by current-induced magnetization switching measurements, and contributes to an ultra-low critical switching current density of 1 mW cm$^{-2}$ in the Pt$_{0.57}$Cu$_{0.43}$ layer. Furthermore, the thermal stability of the Co layer is unaffected by alloying. Finally, Pt–Cu alloy can significantly reduce the power consumption due to a large DL-SOT efficiency and moderate resistivity. The lowest power consumption excluding current shunting is about 4.64 $\times 10^{-11}$ mW cm$^{-2}$ for Pt$_{0.57}$Cu$_{0.43}$ (1.61 $\times 10^{-13}$ mW cm$^{-2}$ for pure Pt). This low power is the best performance among various reported Pt-based SCs, and competitive to other emergent SCs. Moreover, the moderate resistivity of Pt–Cu alloy can mitigate energy dissipation due to current shunting. Therefore, Pt–Cu alloy is expected to be an attractive candidate as the SCS in future SOT-MRAM applications.

6. Experimental Section

Sample Growth and Characterization: The Pt$_x$Cu$_{1-x}$/Co(1)/MgO(2) heterostructures with different Pt concentrations ($x$) were sputter-deposited on SiO$_2$ substrates in a customized ultra-high vacuum magnetron sputtering system with base pressure of $5 \times 10^{-8}$ Torr. The films were deposited via DC or RF magnetron sputtering at room temperature and an Ar growth pressure of 3 mTorr. All the films were capped by Ta(2) as protective layer, which was expected to be fully oxidized under ambient atmosphere. The saturation magnetization of Co was characterized by a VSM.

Device Fabrication and Measurements: All the heterostructures were fabricated into micro-size Hall bar (5 $\mu$m $\times$ 60 $\mu$m) by standard photolithography for electrical measurements. The resistivities were characterized by standard four-point probe measurements. Anomalous Hall resistances were measured by a home-made probe station, which is capable to simultaneously apply in-plane and out-of-plane magnetic field. The electrical measurements were performed with a dc current source (by Keithley 2400) and a voltage meter (by Keithley 2000).

Details of power consumptions from various references can be found in Supporting Information.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

SOT-MRAM, spin Hall effect, spin–orbit torques, spintronics

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