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# Electric field control on single and double Pt/Co heterostructure for enhanced thermal stability

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ABSTRACT

Due to the shielding effect of ferro-metallic materials, electric field control has been limited to magnetic thin films. Here, we show that by applying an electric field to Pt/Co based heterostructures, the modulation of magnetic anisotropy in a multilayer stack is comparable to the modulation observed for a single Pt/Co stack. Additionally, the multilayer provides a ~4 to 5 times increase in thermal stability due to the larger magnetic volume and the increase in perpendicular magnetic anisotropy. The magnetic anisotropy modulation and the increased thermal stability of the multilayer can be attributed to the proximity induced magnetism in the Pt spacer layer between the magnetic Co layers.

## 1. Introduction

Electric field control of magnetic properties in ferro-metallic materials has attracted a great deal of interest in the field of spintronics [1–7]. In particular, the electrical control of magnetic anisotropy has been studied intensively, because it enables the manipulation of the magnetization direction in a ferro-metallic system at a very low energy cost. Recently, many studies have shown that electric field control is able to manipulate the anisotropy energy of a thin layer of ferro-metallic material [8–10]. This is mostly attributed to the voltage controlled magnetic anisotropy (VCMA) effect, where the accumulation and decumulation of electrons at the oxide/ferro-metallic interface causes a change in magnetic anisotropy [11]. In the Thomas-Fermi model, the screening length is determined to be $< 10^{-1}$ nm. As such, the electric field shielding effect of conductive metals limits the VCMA effect to be predominately an interfacial effect [12–14]. However, recent studies of the VCMA effect on thicker ferro-metallic layer revealed that there might be a higher order bulk component to the VCMA effect [15,16]. At the same time, electric field control has also been successfully demonstrated across heavy metal such as Pd and Pt on a Co layer due to the proximity induce magnetism of the heavy metals [5,6,17]. These recent discoveries open a myriad of possibilities for magnetic materials previously thought to be incompatible for electric field control. Such materials include bulk and multi-layered magnetic material, which provides flexibility for material engineering to achieve enhanced performance for electric field control spintronic devices with a high thermal stability.

In this work, we report the findings on the electric field control of Hall crosses using perpendicular magnetic anisotropic (PMA) material consisting of Pt/Co based hetero-structures. We compare the change in thermal stability and electric field modulation between single and double Co layer Hall cross device. The electric field modulation for the double Co layer has a ~80% efficiency compared to the single Co layer, however it has a ~390–520% enhancement in thermal stability. The results expand the practical range of materials which electric field control can be utilized on.

## 2. Results and Discussion

The thermal stability factor can be represented by, $\Delta = K_{eff}\, V/k\, T$, where $K_{eff}$, $V$, $k$ and $T$ represents the effective magnetic anisotropy, volume of magnetic material, Boltzmann constant and temperature respectively. The $\Delta$ increases with additional layers of Co due to the larger magnetic volume, $V$ and $K_{eff}$ is proportional to the anisotropy energy and magnetic saturation ($M_s$) of the material. The combined effect of $V$ and $K_{eff}$ results in an increase in thermal stability, allowing double Pt/Co stack to retain its magnetic properties better than single layer Pt/Co stack after exposure to high temperatures [18]. The Pt/Co based thin films used in this work were measured using a vibrating sample magnetometer (VSM) and the results are presented in Fig. 1. Fig. 1(a) shows the hysteresis loop of the thin films which displays PMA characteristics. The $M_s$ of the various magnetic structures can be extracted from the hysteresis loop and is shown in the table inset. The table also shows the full stack structure of the magnetic multilayer where the numbers in parentheses represent the layer thickness in nanometres. The magnetic volume is estimated with the consideration of

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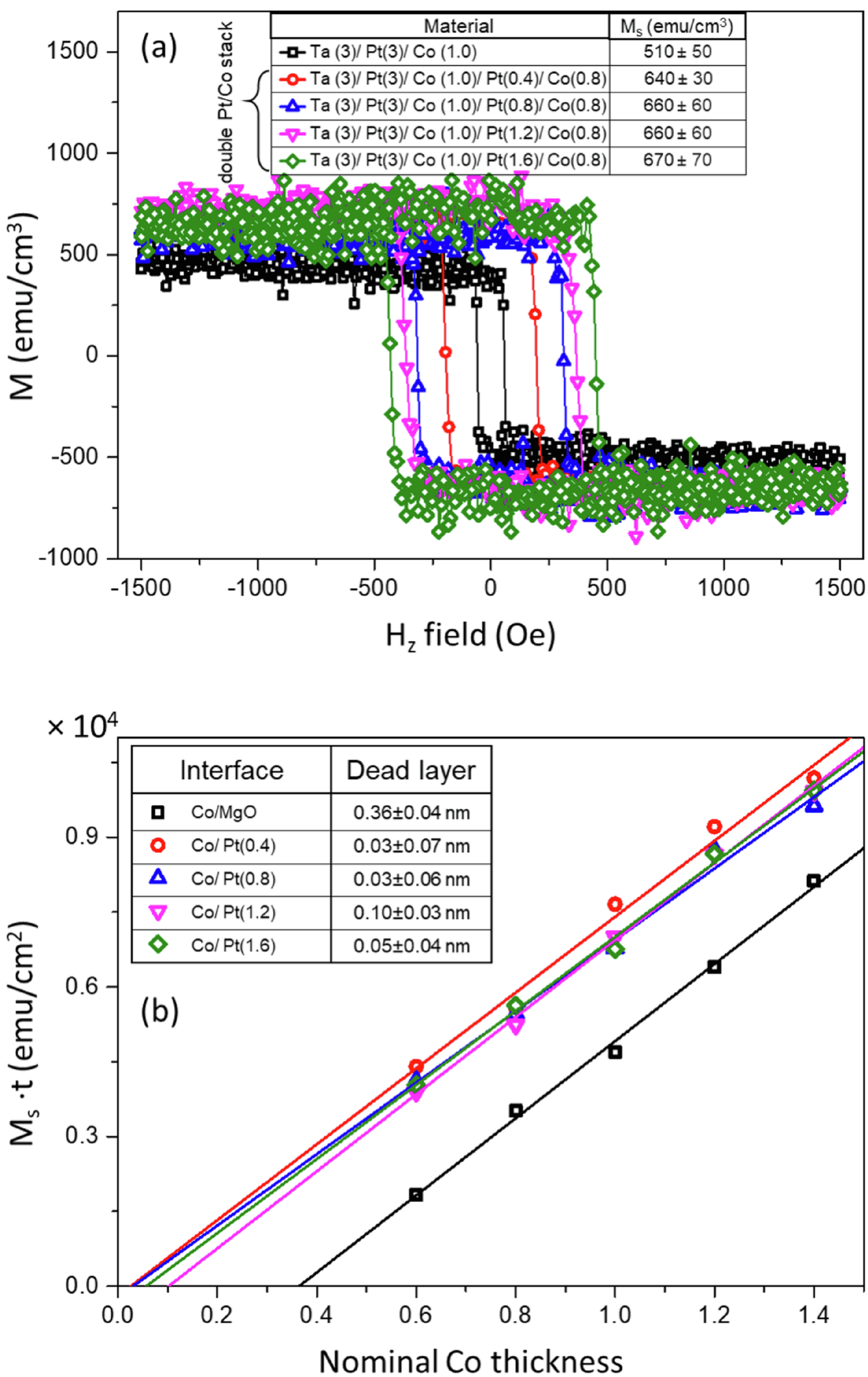



**Fig. 1.** (a) Hysteresis loop obtained using VSM, the table inset shows the magnetic saturation of the thin film stacks shown. (b) Magnetic dead layer obtained by extrapolation of Co thickness with various capping material. The magnetic dead layer enables the determination of the effective magnetic volume used to obtain the magnetic saturation shown in the table inset of (a). The table inset shows the dead layer from the linear fit.

the magnetic dead layer as shown in Fig. 1(b). The magnetic dead layers for the various interfacial layers are also obtained using VSM, where the Co thickness dependence on the $M_s$ indicates the magnetic dead layer of the interface. The Co/MgO interface has a ~0.36 nm dead layer while the Co/Pt (*t*) interface has a dead layer of negligible thickness.

The thin films were patterned with electron beam lithography and anomalous Hall measurements were performed on the resulting Hall crosses. Fig. 2 shows a schematic diagram of the measurement setup where a gate voltage can be applied on the Hall cross device during the Hall resistance measurement. Fig. 3(a) and (b) shows the normalized Hall resistance ($R_H^n$) results under a gate electric field of ( ± 250 MV/m) for a single and double Pt/Co stack respectively. Due to the strong in-plane longitudinal magnetic field ($H_{//}$) of ~14 kOe, there is insignificant $R_H^n$ as the magnetization of the device is mostly along the direction of the $H_{//}$. As the $H_{//}$reduces, the magnetization goes towards the out-of-plane easy axis, resulting in an increase in $R_H^n$. The insets on the left of

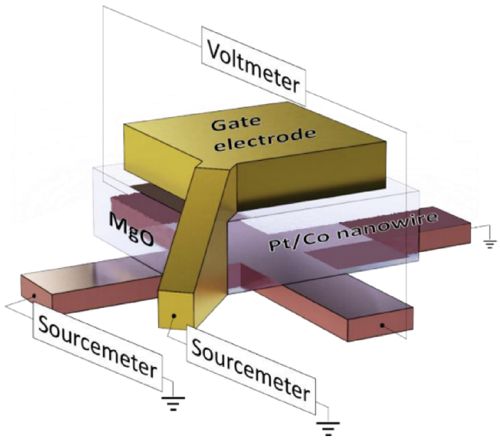



**Fig. 2.** Schematic diagram of the electrical measurement setup for the $R_H^n$ results with electric field control.

Fig. 3(a) and (b) shows the $R_H^n$ dependence with an out-of-plane field ($H_\perp$), which clearly shows the coercivity change due to the electric field modulation. The square hysteresis loop also confirms that the fabricated structure retained its PMA characteristics. The insets on the right of Fig. 3(a) and (b) shows the full $H_{//}$ sweep. The in-plane magnetization of the device $M_{//}^n$ can be estimated from the $R_H^n$ measurements with the equation, $M_{//}^n = sin(arccos(R_H^n))$. The resulting $M_{//}^n$ dependence on the $H_{//}$ is shown in Fig. 3(c) and (d). From the results in Fig. 3(c) and (d), the $K_{eff}$ of the material can be calculated using $K_{eff} = M_s \int H_{//} dM_{//}^n$ [1,5,15].

The $K_{eff}$ dependence on electric field strength for the single and double Pt/Co stacks are shown in Fig. 4(a). The $K_{eff}$ of all the Pt/Co stacks shows a linear relation to the electric field used in this work, where a negative (positive) electric field results in an increase (decrease) in $K_{eff}$. The gradient of the fitted lines represents the electric field modulation of the $K_{eff}$ and is taken to be the magnetic anisotropy modulation efficiency, $dK_{eff}/dE$.

Fig. 4(b) shows the $dK_{eff}/dE$ for the double Pt/Co stacks as a

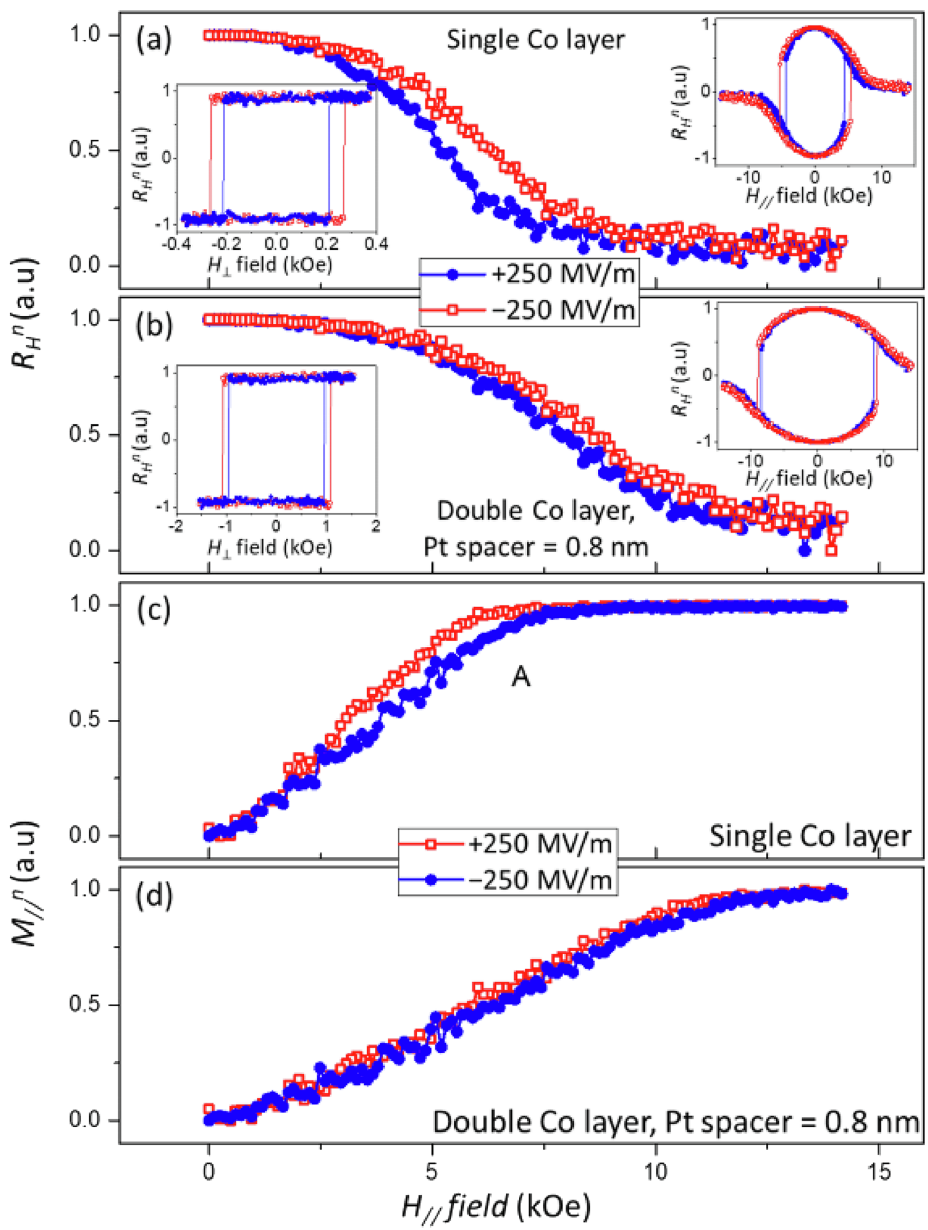
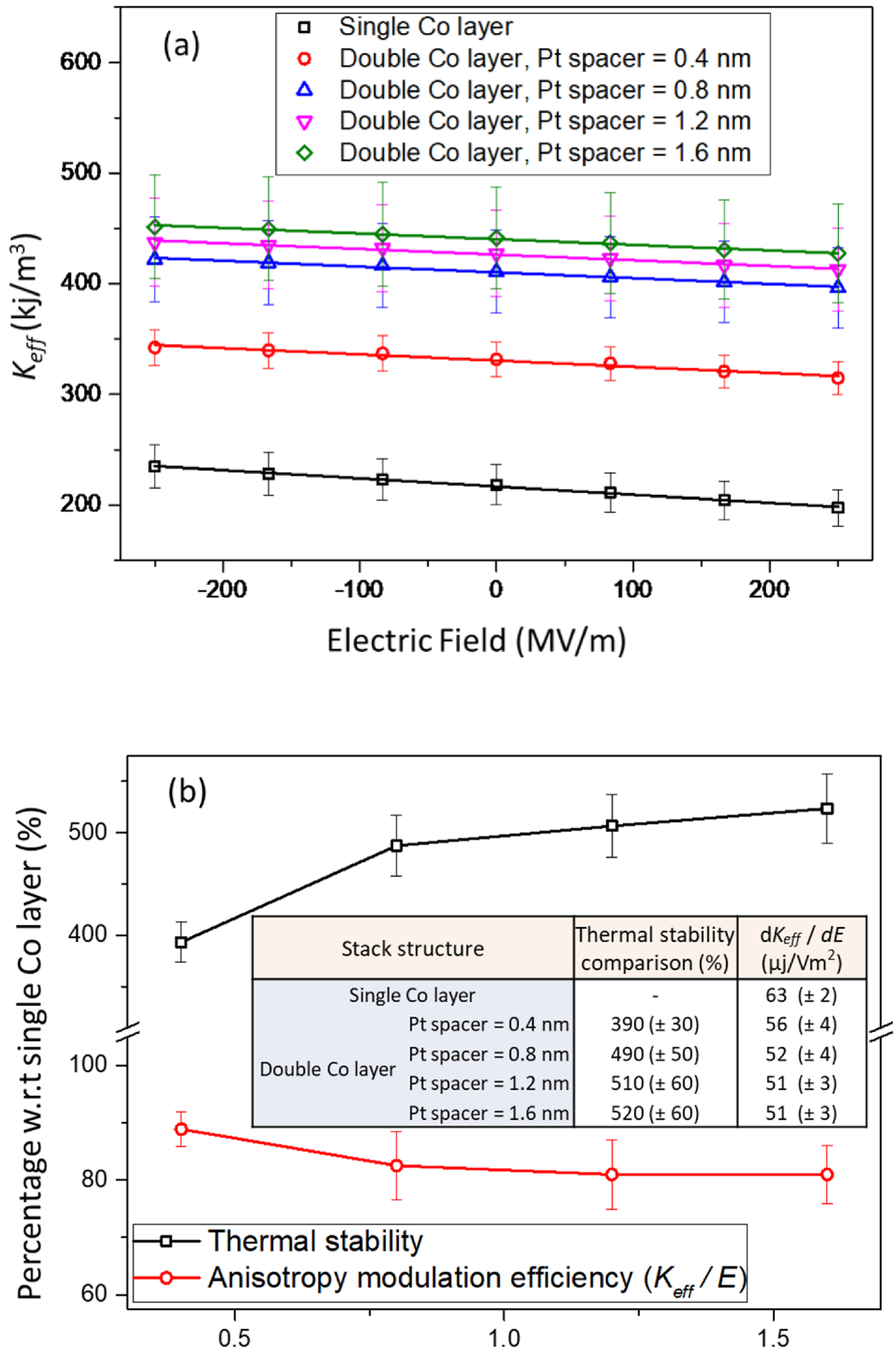



**Fig. 3.** Normalized $R_H^n$ measurements with a sweeping magnetic field longitudinal to the current direction for (a) a single Co layer and (b) double Co layer with a 0.8 nm Pt spacer. The $R_H^n$ measurements are taken with an applied electric field of ± 250 MV/m. The insets for (a) and (b) on the left shows the $R_H^n$ measurements with an out-of-plane magnetic field dependence and the inset on the right shows the full normalized hytherisis loop of the main figure. (c) (d) Normalized in-plane magnetization reproduced from figure (a) and (b).




| Stack structure | | Thermal stability comparison (%) | $dK_{eff}$ / $dE$ (μj/Vm$^2$) |
|---|---|---|---|
| Single Co layer | | - | 63 (± 2) |
| Double Co layer | Pt spacer = 0.4 nm | 390 (± 30) | 56 (± 4) |
| | Pt spacer = 0.8 nm | 490 (± 50) | 52 (± 4) |
| | Pt spacer = 1.2 nm | 510 (± 60) | 51 (± 3) |
| | Pt spacer = 1.6 nm | 520 (± 60) | 51 (± 3) |

**Fig. 4.** (a) $K_{eff}$ as a function of applied electric field for the Pt/Co based Hall crosses. The lines across are a result of linear fittings, all of which gives a negative gradient. (b) Comparison of the $dK_{eff}/dE$ of the Pt/Co based Hall crosses with their thermal stability as obtained from Figure (a). The lines between data points are for visual aid.

percentage to the $dK_{eff}/dE$ obtained from the single Pt/Co stack. Similarly, the thermal stability of the double Co layers is shown as a comparison to the single Co layer. The values of the $dK_{eff}/dE$ and thermal stability are shown in the table of Fig. 4(b). The double Pt/Co stacks show a percentage decrease of $dK_{eff}/dE$ to ~81–89%. However, by only considering the effective magnetic thickness of the top and bottom Co layers, the $dK_{eff}/dE$ of the double Pt/Co stacks would be only ~32% of the single Pt/Co stack if the magnetic anisotropy modulation only occurs for the top Co layer. This result suggests that the magnetic anisotropy modulation occurs for both the top and bottom Co layer. The electric field modulation of the bottom Co layer can be attributed to the proximity induced magnetism of the Pt spacer layer, where the growth of Pt on Co has a larger proximity induced magnetism than Co on Pt. [19] There is also a marginal decrease in $dK_{eff}/dE$ with thicker Pt spacer layer resulting in a change of ~8% between Pt spacer thickness of 0.4 nm and 1.6 nm. The demagnetization field between the top and bottom Co layer does not contribute significantly to the anisotropy modulation of the bottom Co layer. This is validated using micromagnetic simulations as shown in the supplementary material.

The difference in $dK_{eff}/dE$ between single and double Co layer is modest in comparison with the increase in the thermal stability of the double Co layer. The double Pt/Co stack includes a larger magnetic volume which increases the thermal stability by a factor of ~2.2. Only the volume of the magnetic Co layers and not the Pt layer is considered for the thermal stability calculations in this work. The increase in volume to improve thermal stability is further supplemented by the increase in $K_{eff}$ as shown in Fig. 4(a). This increase in $K_{eff}$ is possibly due to the additional Pt (1 1 1) layer between the Co layers which encouraged a larger magneto crystalline anisotropy [20]. The combined effects of the increased volume and $K_{eff}$ allows the thermal stability of the double Co layer to be ~3.9–5.2 times larger than the single Pt/Co stack. When a thicker Pt spacer layer is used, the increase in magneto crystalline anisotropy is enhanced which leads to further increases in thermal stability by virtue of the increased $K_{eff}$. There was also no observed oscillating behaviour with the variation of Pt spacer thickness, implying that there is no RKKY coupling-like effect between two ferromagnetic layer [21,22].

## 3. Conclusion

In summary, electric field control for single and double Pt/Co layers was performed and the results suggests that the electric field control in this work is not merely an interfacial effect at the ferro-metallic/insulator interface. The electric field modulation of the bottom Co layer can be attributed to the proximity induce magnetism of Pt, allowing the double Pt/Co structures to have > 80% $dK_{eff}/dE$ as compared to a single Co layer. The minimal decrease of $dK_{eff}/dE$ coincides with a huge ~390–520% increase in thermal stability for double Pt/Co structures. The results presented in this work open the possibility of electric field control on high thermal stability multilayer ferro-metallic material.

## 4. Methods

Thin film growth on thermally oxidised silicon dioxide substrates were carried out by magnetron sputtering with a base pressure of $< 3 \times 10^{-8}$ Torr. Device fabrication was accomplished using electron beam lithography, where the Hall cross structure is fabricated using a negative resist (MaN2401) with argon ion milling and lift-off technique. The oxide layer and electrodes were fabricated using a positive resist (PMMA) and lift-off technique. The deposition of the oxide and electrodes were carried also carried out in a magnetron sputtering chamber with a base pressure of $< 3 \times 10^{-8}$ Torr.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jmmm.2019.165448.

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