Anomalous coercivity enhancement with temperature and tunable exchange bias in Gd and Ti co-doped BiFeO$_3$ multiferroics

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Figure 1(S1) (a) demonstrates the $M - H$ hysteresis loops of $\text{Bi}_{0.9}\text{Gd}_{0.1}\text{Fe}_{1-x}\text{Ti}_x\text{O}_3$ ($x = 0.00$) sample measured at different temperatures. This is a Ti undoped and only Gd doped $\text{Bi}_{0.9}\text{Gd}_{0.1}\text{FeO}_3$ multiferroic material. The asymmetric shift along the field axes are shown in the enlarged view at temperatures: (b) 20 K (c) 50 K (d) 100 K (e) 150 K (f) 200 K (g) 250 K and (h) 300 K. Figure 2(S2) (a) demonstrates the $M - H$ hysteresis loops of $\text{Bi}_{0.9}\text{Gd}_{0.1}\text{Fe}_{1-x}\text{Ti}_x\text{O}_3$ ($x = 0.20$) sample measured at different temperatures. The asymmetric shift along the magnetic field axes are also shown separately in the enlarged view at temperatures: (b) 20 K (c) 50 K (d) 100 K (e) 150 K (f) 200 K (g) 250 K and (h) 300 K.

The value of the exchange bias field at different temperatures in $\text{Bi}_{0.9}\text{Gd}_{0.1}\text{Fe}_{1-x}\text{Ti}_x\text{O}_3$ ($x = 0.00$ and 0.20) compositions are shown in table 1.
FIG. 1: (S1) (a) The $M - H$ hysteresis loops of Bi$_{0.9}$Gd$_{0.1}$Fe$_{1-x}$Ti$_x$O$_3$ ($x = 0.00$) sample measured at different temperatures. (b-h) An enlarged view of the low-field M-H hysteresis loops at temperatures: (b) 20 K (c) 50 K (d) 100 K (e) 150 K (f) 200 K (g) 250 K and (h) 300 K.
FIG. 2: (S2) (a) The $M - H$ hysteresis loops of bulk $\text{Bi}_{0.9}\text{Gd}_{0.1}\text{Fe}_{1-x}\text{Ti}_x\text{O}_3$ ($x = 0.00$) material measured at different temperatures. (b-h) An enlarged view of the low-field $M-H$ hysteresis loops at temperatures: (b) 20 K (c) 50 K (d) 100 K (e) 150 K (f) 200 K (g) 250 K and (h) 300 K.
TABLE I: The table shows the exchange bias fields of $\text{Bi}_{0.9}\text{Gd}_{0.1}\text{Fe}_{1-x}\text{Ti}_x\text{O}_3$ ($x = 0.00$ and 0.20) compositions at different temperatures.

| $x$ | $H_{EB}$ (Oe) |
|-----|----------------|
|     | $T = 20\text{ K}$ | $T = 50\text{ K}$ | $T = 100\text{ K}$ | $T = 150\text{ K}$ | $T = 200\text{ K}$ | $T = 250\text{ K}$ | $T = 300\text{ K}$ |
| 0.00 | 8 | 70 | 101 | 122 | 122 | 143 | 31 |
| 0.20 | 7 | 64 | 61 | 80 | 26 | 64 | 33 |

The $M - H$ hysteresis loops of sample $x = 0.10$ measured at 150 K after being cooled from 300 K in zero field and then in separate experiments in the presence of various cooling magnetic fields are presented in figures 3(S3) (a). The enlarged views, figures 3(S3) (b-e) demonstrate the asymmetric shifting along the field axes. Similarly, hysteresis loops measured at 250 K after being cooled from 300 K in zero field and then in the presence of various cooling magnetic fields are shown in figures 4(S4)(a). The enlarged views, figures 4(S4) (b-e) show the asymmetric shifting of the hysteresis loops along the magnetic field axes.
FIG. 3: (S3) (a) The $M - H$ hysteresis loops of sample $x = 0.10$ measured at 150 K by applying cooling magnetic fields. (b-h) The enlarged views show the effect of cooling magnetic field on asymmetric shifting of the hysteresis loops.
FIG. 4: (S4) (a) The $M - H$ hysteresis loops of sample $x = 0.10$ measured at 250 K in presence of cooling magnetic fields. (b-h) The enlarged views demonstrate the effect of cooling magnetic field on asymmetric shifting of the field axes.