Quasipolaron Surface Polarization in Bismuth Ferrite

Jiarui Zhang,1 Yongbao Cui,2 Nannan Liu,3 Qi Qi,1 Rui Huang,1 Kai Chen,1,4,‡ Laijun Liu,2,† Zhida Han,5,‡ and Guoliang Yuan3

1 School of Science, Nanjing University of Science and Technology, Nanjing 210094, People’s Republic of China
2 Guilin University of Technology, Guilin 541004, People’s Republic of China
3 School of Materials Science and Engineering, Nanjing University of Technology, Nanjing 210094, People’s Republic of China
4 MIIT Key Laboratory of Semiconductor Microstructure and Quantum Sensing, Nanjing University of Science and Technology, Nanjing 210094, People’s Republic of China
5 School of Electronic and Information Engineering, Changshu Institute of Technology, Changshu 215500, People’s Republic of China

(Received 29 July 2022; revised 21 September 2022; accepted 11 October 2022; published 8 November 2022)

With the introduction of a not fully screened polarization that leads to three magnetic subdomains nested in one ferroelectric domain, we identify it as the quasipolaron surface polarization in the electrode effect of bismuth ferrite. The remanent polarization at 40 Hz is about 439 $\mu$C/cm$^2$ in the dielectric hysteresis loop of a reverse S shape, accompanying the antiferromagnetic one of an S shape, which reveals that the surface is an indispensable part in spintronics.

DOI: 10.1103/PhysRevApplied.18.L051002

The room-temperature existence of long-range coupled ferroelectric and antiferromagnetic orders in multiferroic bismuth ferrite (BiFeO$_3$) manifests itself as a variety of attractive physical phenomena and technological potentials. Recently, within a single ferroelectric domain of about $6 \times 6 \mu$m in the last 30–50 nm of a (001)-oriented single crystal to its surface, triple-$k$ magnetic subdomains of about $600 \times 600$ nm have been observed, which is due to a bulk $k$ cycloid destabilized at the surface by a not fully screened polarization through magnetoelectric coupling [1]. The leakage polarization is unclear but important for the domain structure, when the nested domain structure offers a utilization for spintronics.

In BiFeO$_3$ with a slightly distorted rhombohedral structure (space group $R3c$), the Bi ions displace off-center about 0.61 Å for large dipoles of approximately 8.78 Debye units (D), pointing along one of the $\langle 111 \rangle_r$ directions in the pseudocubic lattice. The broad distance distribution of 2.25–3.5 Å between Bi and neighbor O ions accommodates the disorder of local BiO$_6$ octahedra, with different octahedra rotation angles and Bi—O bond lengths [2]. The Bi sublattice is significantly more disordered than the Fe sublattice [3]. In FeO$_6$ octahedra with obvious short (1.92 Å) and long (2.15 Å) Fe—O bonding distances, the Fe ions shift off-center about 0.22 Å along the same directions for small dipoles of approximately 3.16 D. Oxygen ions are, in part, covalently bonded by O $p$ states to both Bi and Fe ions [4–6], leading to $\langle 111 \rangle_r$-oriented “--O–Bi–O–Fe–O--” dipole chains of alternating large and small dipoles, which are with a period of approximately $\sqrt{3} \times 6 \times 6 \mu$m. Along $\langle 111 \rangle_r$ directions, the distance between the small dipole and the neighboring large one is in the range from approximately 3.08 to approximately 3.92 Å. Importantly, the disorder of local BiO$_6$ and FeO$_6$ octahedra provides crystalline positions of the energy double potential well for macroscopic polarization-switching dynamics. The existence of dipole chains is also suggested by the density-functional calculations of oxygen, bismuth, and iron vacancies [7]. The parallel branches of these dipole chains constitute the polarization, $P$, of ferroelectric domain along the [111]$_r$ axis, which makes the in-plane component on the (111)$_r$ surface plane. Although the strong coupling among the dipoles keeps the ferroelectric order against the thermal destruction up to the structural transition temperature of $T_c = 1033$ K, the multibody sensitivity of dipole chains to the ion number, the correlation strength, and the local crystal field result in different average values of spontaneous ferroelectric polarization.
$P_5$ (average dipole moment per unit volume), in the bulk, the film, the two-dimensional system, and the nanomaterial. The magnetic ground state is the antiferromagnetic cycloid, the plane of spin rotation in the cycloid is perpendicular to $P_5$, and, thus, the 3$d^5$ spins of Fe ions in dipole chains are perpendicular to the $P_5$ branch of dipole chains. In the $k$ direction also as the transverse direction of the branch, the superexchange interaction assists the strain and the relativistic Dzyaloshinskii-Moriya interaction, to correlate them up to the Neél temperature of $T_N = 643$ K. The dipole chains with different lengths have Fe 3$d^5$ spins of different quantities, and to some extent have an effect on the average magnetic moment per unit cell. Thus, the three-dimensional dipole-chain network carrying the spins is formed as the bulk polarization at room temperature for the ferroelectricity [8–11]. The net-...

The material and diameter of circular electrodes have an obvious effect on the weak-field polarization, as a sign of which is the real part of the complex dielectric value, $\varepsilon'$, i.e., the scientific form of industrial permittivity. For the Ag electrodes, a larger diameter reduces the value of $\varepsilon'$, as shown in Fig. 1(a). The reduction is independent of frequency from $10^2$ to $10^7$ Hz, and the relative change defined as $(\varepsilon'/Ag:Au:1.5$ or $Ag:Au:3.0 - \varepsilon'Ag:Au:6.0)/\varepsilon'Ag:6.0$ is as large as 83%, as shown in Fig. 1(b). However, the frequency-independent effect is not observed for the Au electrode samples, as shown in Figs. 1(c) and 1(d). For the Au:3.0 sample, an increased electrode diameter increases the value of $\varepsilon'$ above the characteristic frequency of about $10^5$ Hz, but decreases the value at lower frequencies. Also, the Au:6.0 sample shows a similar effect, the characteristic frequency being about $10^6$ Hz.

To identify the weak-field polarization, complex plots of $\varepsilon'$ and $\varepsilon''$ for all samples in a wide frequency range from 40 to $10^8$ Hz are used, as shown in Fig. 2, where $\varepsilon''$ is the imaginary part of the complex dielectric value. There is a transition frequency (TF), at which two different decreasing and increasing trends of $\varepsilon''$ with increasing frequency are combined. For the Ag electrode samples...
FIG. 2. Complex plots of $\varepsilon'$ and $\varepsilon''$ for all samples.

[Figs. 2(a)–2(c)], the TF is $10^{6.72}$ Hz for the Ag:1.5 sample, $10^{6.68}$ Hz for the Ag:3.0 one, and $10^{6.62}$ Hz for the Ag:6.0 one, respectively. Thus, increasing electrode diameter decreases the TF, and then increases the higher-frequency response range of the polarization. The same phenomenon occurs for all of the Au electrode samples [Figs. 2(d)–2(f)]. For magnetoimpedance spectroscopy on the films, the equivalent circuit-fitting method, in a phenomenological way, shows two types of polarizations, which are due to the intrinsic contribution and the extrinsic interface one [12]. Within the frame of the classic dielectric theory [13], the intrinsic contribution is the dipole-chain network, and the extrinsic one is the interface Schottky-type barrier, which is, however, ambiguous for dielectric species. Quantum dielectric physics, further, gives a clearer hint that the barrier results from the electrostatic potential field of polaronlike 3d electrons pinned at grain surfaces [14]. The local polarization of these electrons is proposed by the superexchange theory [15], and in bismuth ferrite is particularly highlighted by the non-$d^0$ ferroelectric polarization of the semicovalent superexchange model [16]. The maximum strength of the superexchange interaction in the half-filling $t_2^\infty$ configuration of Fe 3d$^5$ electrons and the strong interatomic hybridization by Fe 3d and O 2p orbital overlap enhance the Born effective charge, with decreasing the moment on Fe ions through the covalent exchange pairing and corroborating the antiferromagnetic pairing’s facilitation to the formation of singlet states, and thus resulting in the long-range ferroelectric order in Fe 3d$^5$ multiorbital manifold. The superexchange endows BiFeO$_3$ with a 3d$^5$-electron-driven ferroelectric polarization, which is as large as approximately 53 μC/cm$^2$ for the total polarization (approximately 100 μC/cm$^2$) when the polarization induced by the dipole chains is estimated as approximately 47 μC/cm$^2$. The hopping routes for the superexchange include ligand holes, and terminate at the orbitals in the surface unit cells. We name these 3d electrons as quasipolarons, and thus the quasipolaron surface polarization may be a candidate for the leakage polarization. Increased electrode diameter means that more quasipolarons are involved in the dielectric polarization at high frequencies, which requires more excitation energy, and then the decreased TF is understandable for the wider high-frequency response range. Notably, the quasipolarons of the surface polarization originate from the Fe 3d$^5$ electrons of dipole chains, and macroscopically the TF confirms that the quasipolaron surface polarization is correlated to the bulk one of the dipole-chain network.

The quasipolaron surface polarization at higher frequencies is affected by the electrode characteristics, and via correlation, may transfer the effect to the bulk polarization of the dipole-chain network under lower-frequency strong fields. To validate this, we present the frequency-dependent dielectric hysteresis loops, i.e., the polarization-voltage loops, when an excitation signal of periodic and triangular wave with the same amplitude of 3600 V is applied, and all of the current range is set as 100 mA. The chosen frequency range from 40 to $10^3$ Hz encompasses the response of the bulk polarization, as suggested by weak-field dielectric spectra. Figures 3(a) and 3(d)–3(f) show that the almost frequency-independent loops are in the shape of a “banana” for samples Ag:1.5, Au:1.5, Au:3.0, and Au:6.0, with a polarization as large as approximately 4 μC/cm$^2$. The shape suggests that the loops are dominated by leakage currents, which results from the mixed valence of Fe$^{2+}$ and Fe$^{3+}$ within the frame of the semicovalent superexchange model. The measured current is more underflow than 100 mA, and the samples are lossy dielectrics [17]. When the dielectrics are measured as the internal layer of a parallel-plate capacitor with two metal electrodes, we summarize the switched charge $Q$, the measured current $I$, and $P$ in one period, $T$ (1/frequency), as the following:

$$Q = \left( \int \varepsilon I dT \right) A = \left( \int I_{\text{bulk}} dT + \int I_{\text{leakage}} dT \right) A = (P_{\text{bulk}} + P_{\text{surface}}) A,$$

(1)
shows dielectric hysteresis loops of the reverse
shape for sample Ag:3.0. Sample Ag:6.0 also
occurs for sample Ag:1.5 and sample Ag:3.0 [Figs. 3(a)
and 3(b)]; however, the shape of the dielectric hysteresis
loop changes from a “banana” shape for sample Ag:1.5 to
a reverse S shape for sample Ag:3.0. Sample Ag:6.0 also
shows dielectric hysteresis loops of the reverse S shape,
as shown in Fig. 3(c). Although the measured current is
underflow in sample Ag:3.0, that in sample Ag:6.0 is nei-
ther underflow nor overflow, and therefore the measured
polarization-voltage loop is reliable. We notice that the
recorded largest voltage of approximately 400 V is much
smaller than the applied amplitude of 3600 V, and this
screening effect confirms the existence of quasipolaron
surface polarization.

Interesting, the remanent polarization, \( P_r \), at 40 Hz
is about 439 \( \mu C/cm^2 \), which is the largest value.
The characteristic remanent polarization, \( P_{cr} \), is defined as
follows:

\[
P_{cr} = \frac{|P_{r-} - P_{r+}|}{2},
\]

where \( P_{r+} \) and \( P_{r-} \) are the positive and negative remanent
polarizations, respectively.

Then, it is dependent on the excited frequency
[Figs. 4(a) and 4(b)], as follows:

\[
lg(P_{cr}) = -lg(f) + 1.87 \quad \text{for sample Ag:3.0},
\]

\[
P'_{cr} = P'_0(E'_0/hf) = P'_0(E'_0/h\omega)
\]

\[
(P'_0 = 10^{1.87} \tau'_0, E'_0 = h/\tau'_0, \text{ and } \omega = 2\pi f),
\]

\[
lg(P_{cr}) = -lg(f) + 4.26 \quad \text{for sample Ag:6.0},
\]

\[
P''_{cr} = P''_0(E''_0/hf) = P''_0(E''_0/h\omega)
\]

\[
(P''_0 = 10^{4.26} \tau''_0, E''_0 = h/\tau''_0, \text{ and } \omega = 2\pi f),
\]

where \( P'_0 \) is the polarization of surface ground-state
quasipolarons, \( E'_0 \) is the ground-state energy, \( h \) is the
Planck constant, \( f \) is the applied voltage frequency, \( h \) is
the reduced Planck constant, \( \omega \) is the angular frequency,
and \( \tau'_0 \) is the retention time of the ground-state quasipo-
larons in sample Ag:3.0. The same applies to \( P''_0, E''_0, \) and
\( \tau''_0 \) for sample Ag:6.0.

Finally, they are summarized as follows:

\[
P'_l = P'_0(E'_l/hf) = P'_0(E'_l/h\omega)
\]

\[
(l = 1.87 \text{ for sample Ag:3.0 and } 4.26 \text{ for sample Ag:6.0}).
\]

By increasing the excitation frequency, the entities of
dipole chains are excited from the ground state to fewer
states of higher energy level, which reduces the quasipo-
laron occupy quantity to \( P_{cr} \), accompanying a screening
effect whereby the polarization contribution at lower-
energy-level states is shielded. The higher the energy
level, the fewer the states and they are quasiconstant
or continuous. Thus, we induce the dielectric hysteresis
loop of the reverse S shape as the reverse ferroelectric-
ity, which is dominated by the quantum excited states.
To further distinguish the reverse ferroelectricity from fer-
roelectricity, we plot the time dependence of measured

FIG. 3. Polarization-voltage loops under the same voltage of
3600 V at different frequencies for all samples.

where \( P_{bulk} \) is the bulk polarization, \( P_{surface} \) is the surface
polarization, and \( A \) is the lateral area of the capacitor. We
assume that all basic properties follow the linear superposi-
tion rule and choose the plus sign to describe the relation of
the same kind. Further, the plus sign shows the correlation
between the remanent bulk polarization of dipole-chain
network and the remanent surface polarization of quasipo-
larons. By correlation, an increased electrode diameter
decreases both the value and the range of
\( P \) from that of sample Au:1.5, then to that of sample Au:3.0, and finally
to that of sample Au:6.0, as shown in Figs. 3(d)–3(f). The
trend seems to be that the value range is inversely pro-
portional to the electrode diameter. A similar trend also
occurs for sample Ag:1.5 and sample Ag:3.0 [Figs. 3(a)
and 3(b)]; however, the shape of the dielectric hysteresis
loop changes from a “banana” shape for sample Ag:1.5 to
a reverse S shape for sample Ag:3.0. Sample Ag:6.0 also
shows dielectric hysteresis loops of the reverse S shape,
as shown in Fig. 3(c). Although the measured current is
underflow in sample Ag:3.0, that in sample Ag:6.0 is nei-
ther underflow nor overflow, and therefore the measured
polarization-voltage loop is reliable. We notice that the
FIG. 4. Frequency dependence of $P_{cr}$ and time dependence of measured current in one period for the sample Ag:3.0 (a and c) and the sample Ag:6.0 (b and d), respectively. Magnetic hysteresis loops for all samples (e and f).

As shown in Figs. 4(a) and 4(b), the dependence shows a doorframe shape, which is different from the M shape of ferroelectricity. The large current in Fig. 4(b) shows that compared with those in other samples, more quasipolarons in sample Ag:6.0 are excited to involve the surface polarization. And these quasipolarons are with spins, and thus sample Ag:6.0 should show a better magnetic property, which is self-consistently confirmed by the magnetic hysteresis loop of S shape, as shown in Figs. 4(e) and 4(f). Under the same magnetic field of 10 kOe, these quasipolarons improve the moment of sample Ag:6.0 by up to 37% compared with those of other samples.

In summary, the quasipolaron surface polarization is revealed as the origin for the nested domain structure, when the electrode effect is compared, and the concepts of quasipolaron and reverse ferroelectricity are introduced. More quasipolarons are pinned at the surface per unit area, increasing the surface density of antiferromagnetically ordered spins. The largest remanent polarization and the better antiferromagnetic properties show that the surface is important for spintronics.
Acknowledgments.—J.Z. and Y.C. contributed equally to the work. K.C. acknowledges the support from the National Natural Science Foundation of China (Grant No. 11004106) and the Fundamental Research Funds for the Central Universities (Grant No. 30920021144).