Electronic transitions and dielectric functions of relaxor ferroelectric Pb(In1/2Nb1/2)O3-Pb(Mg1/3Nb2/3)O3-PbTiO3 single crystals: Temperature dependent spectroscopic study


View online: http://dx.doi.org/10.1063/1.4870426
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/104/13?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

Broadband inelastic light scattering study on relaxor ferroelectric Pb(In1/2Nb1/2)-Pb(Mg1/3Nb2/3)O3-PbTiO3 single crystals

Electrocaloric properties in relaxor ferroelectric (1−x)Pb(Mg1/3Nb2/3)O3−xPbTiO3 system

Temperature-dependent Raman scattering and multiple phase coexistence in relaxor ferroelectric Pb(In1/2Nb1/2)O3-Pb(Mg1/3Nb2/3)O3-PbTiO3 single crystals

Temperature-dependent dielectric functions and interband critical points of relaxor lead hafnate-modified PbSc1/2Ta1/2O3 ferroelectric ceramics by spectroscopic ellipsometry
Appl. Phys. Lett. 102, 151908 (2013); 10.1063/1.4802205

Phase transition behaviors in relaxor ferroelectric [001]-poled Pb(In1/2Nb1/2)O3-Pb(Mg1/3Nb2/3)O3-PbTiO3 single crystals studied by Brillouin light scattering and dielectric spectroscopies
Electronic transitions and dielectric functions of relaxor ferroelectric Pb(In$_{1/2}$Nb$_{1/2}$)O$_3$-Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$-PbTiO$_3$ single crystals: Temperature dependent spectroscopic study

J. J. Zhu (诸佳俊), 1,2 J. Z. Zhang (张金忠), 1,2 G. S. Xu (许桂生), 3 X. L. Zhang (张小龙), 1
Z. G. Hu (胡志高), 1,4 and J. H. Chu (褚佳俊) 1,2

1Key Laboratory of Polar Materials and Devices, Ministry of Education, Department of Electronic Engineering, East China Normal University, Shanghai 200241, China
2National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China
3R&D Center of Synthetic Crystals, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, China

(Received 6 February 2014; accepted 23 March 2014; published online 1 April 2014)

Optical properties and phase transitions of Pb(In$_{1/2}$Nb$_{1/2}$)O$_3$-Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$-PbTiO$_3$ (PIN-PMN-PT) crystals near morphotropic phase boundary (MPB) have been investigated by temperature dependent transmittance and reflectance spectra. Three critical point energies $E_p = 3.17–3.18$ eV, $E_a = 3.41–3.61$ eV, and $E_d = 4.74–4.81$ eV can be assigned to the transitions from oxygen $2p$ to titanium $d$, niobium $d$, and lead $6p$ states, respectively. They show narrowing trends with increasing temperature, which can be caused by thermal expansion of the lattice and electron-phonon interaction. Deviation from the linear behaviors can be observed from $E_d$ and $E_p$ versus PT concentration, indicating a complex multiphase structure near MPB region. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4870426]

Relaxor ferroelectrics with peculiar characteristics of ferroelectricity and piezoelectricity can be used in the fields for sensors, nonvolatile random access memories, electro-optic modulators, pyroelectric detectors, and micro-electromechanical systems. Ferroelectricity in lead (Pb)-based relaxors with ABO$_3$ perovskite structure is driven mainly by the stereochemical activity of Pb. Nevertheless, the B-site ions primarily affect morphotropic phase boundary (MPB) and facile polarization rotation, providing the disorder and leading to relaxor ferroelectricity. Ionic size effects, A-site-oxygen (O) and B-site-O hybridizations play an important role in competing structural and polar instabilities of perovskites, including the complexity of physical mechanism. The solid solutions of PbMg$_{1/3}$Nb$_{2/3}$O$_3$-PbTiO$_3$ (PMN-PT) crystallize in a complex ABO$_3$ perovskite structure, where B-site ions occupy the same crystallographic site in the structure with a complex energy distribution. It has a higher piezoelectric response than that of conventional piezoelectric PbZr$_x$Ti$_{1-x}$O$_3$ (PZT) ceramics, especially near the MPB region. Note that a transition occurs from a linear behavior were observed in PMN below the burn's temperature due to the formation of static or slowly moving polar nano-regions. This decreases the thermal stability of dielectric and piezoelectric properties and reduces the operation temperature range of the devices, which becomes a critical limitation for applications.

Fortunately, it was found that Pb(In$_{1/2}$Nb$_{1/2}$)O$_3$-Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$-PbTiO$_3$ (PIN-PMN-PT) systems offer a larger coercive field ($E_c \geq 5$ kV/cm) and higher degree of structural instabilities ($T_{R-T} \geq 135^\circ$C), while the piezoelectric performance is comparable to that of PMN-PT systems. Moreover, temperature dependence of dielectric and piezoelectric properties is more stable, which makes PIN-PMN-PT ternary systems the most promising materials for future device applications. Recently, we reported bandgap narrowing and widening trends with increasing temperature for PIN-PMN-PT crystals near MPB below room temperature (RT). However, the dielectric functions and electronic band structures at high temperatures have not been fully clarified. Generally, transmittance spectra can provide optical bandgap (OBG), dielectric functions, absorption characteristics, and band tail state behavior by comparing the reasonable dispersion model to experimental spectra. Similarly, spectral reflectance technique can be used to investigate the electronic band energy above the OBG, which cannot be detected by transmittance technique due to the strong absorption (Fig. 1). The reliability of the inverse synthesis method mainly depends on the validity of the optical model and the fitting statistics. Therefore, one can take advantages of solid state spectroscopy to further study the promising ternary system. In the Letter, we estimated the interband critical point energies of PIN-PMN-PT crystals by combining spectral transmittance with reflectance located in the ultraviolet energy range. Effects from temperature and PT concentration on electronic band structure have been discussed in detail.

PIN-PMN-PT single crystals were grown using a vertical Bridgman technique. The samples were cut perpendicular to the (001) direction. The nominal concentration of xPIN-(1–x–y)PMN-yPT crystals was $x \sim 0.27–0.28$ and $y \sim 0.29–0.35$. All PIN-PMN-PT crystals were double-side polished with a mechanical polishing process to smooth the
This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 222.66.117.15 On: Mon, 20 Oct 2014 07:51:03

FIG. 1. (a) Reflectance and (b) transmittance spectra of PIN-PMN-0.29PT crystal at the temperatures of 303 K, 373 K, and 453 K, respectively. The experimental (dots) and calculated (solid lines) reflectance spectra of (c) PIN-PMN-0.29PT, (d) PIN-PMN-0.31PT, (e) PIN-PMN-0.33PT, and (f) PIN-PMN-0.35PT crystals at 303 K and 453 K, respectively. The arrows indicate the corresponding interband transitions.

The normal-incident transmittance spectra and near-normal incident (about 8°) reflectance spectra were measured by a double beam ultraviolet-infrared spectrophotometer (PerkinElmer UV/VIS Lambda 950) at the wavelength range of 2650–190 nm (0.5–6.5 eV) with a spectral resolution of 2 nm. The samples were mounted on a heating stage (Bruker A511), which can be varied from RT to 453 K with a step of ±1 K.

Figs. 1(a) and 1(b) show reflectance and transmittance spectra of PIN-PMN-0.29PT single crystal from near infrared to ultraviolet regions at different temperatures, respectively. With increasing photon energy, the transmission decreases quickly and falls down to zero at about 3.18 eV, indicating an optical absorption edge. This process excites an electron from the filled valence band to an elevated state of the conduction band. The first principle study reveals that the conduction band edge comes primarily from niobium (Nb) orbitals associated with each octahedron while Mg/In character is distributed through the O 2p orbitals in the valence bands.[13] Electronic band structures of ABO3 perovskite are closely relative to the BO6 octahedron and sensitive to the B-site atom concentration. The B-site ion plays more important role in the refined energy level as compared to the A-site. For PIN-PMN-PT crystals, Mg2+, Nb5+, In3+, Ti4+ ions occupy the octahedral B site disorderly, giving rise to the disorder and the random fields. The substitution of Ti4+ for the complex (In1/3/Nb1/3)3+ and (Mg1/3/Nb2/3)3+ ions prefers the development of macro-polar domains from nanopolar regions inherently present in relaxors. The nanoregions, domain structure, and order/disorder state of the B-site cation structure have strong effects on the dielectric functions of the crystal.

The main spectral features in Figs. 1(a) and 1(b) are centered at 3.18 ± 0.02, 3.62 ± 0.07, and 4.75 ± 0.02 eV, which are labeled as $E_p$, $E_a$, and $E_b$, respectively. These features have been also reported in ferroelectrics PbTiO3 PT, PbZrO3 (PZ), PZT, (1−x)Pb(Sc1/2Ta1/2)O3-xPbHfO3 (PSTH), and Pb(ZrSnTi)O3 (PZST).[14-17] The structures shift to a lower energy side and become broader with increasing temperature. According to the experimental data as well as local density approximation electronic band structure calculations, the critical point energies for PT at 3.78, 4.00, and 4.93 eV are attributed to $X_{5c} - X_{5v}$ transition, $X_{6c} - X_{6v}$ transition, and $X_{8c} - X_{8v}$ transition, respectively.[16,17] An anticrossing of critical point energies for PZT occurred, which is due to the coupling between $X_{5v}$ and $X_{6v}$ bands, arising from intrinsic alloy disorder. The potential fluctuation caused by alloy disorder induces a coupling between the degenerate bands.[16]

Figs. 1(c)–1(f) show reflectance spectra of PIN-PMN-PT crystals at 303 K and 453 K, respectively. Two obvious peak positions $E_a$ and $E_b$ are located at 3.62 eV and 4.75 eV for PIN-PMN-0.29PT crystal, which are consistent with the fitted peak position energies $E_{p1}$ (3.61 ± 0.07 eV) and $E_{p2}$ (4.74 ± 0.02 eV), as shown in Table I.

Table I. Parameter values of the double Tauc-Lorentz dispersion model for the PIN-PMN-PT crystals are obtained by simulating the near-infrared-ultraviolet reflectance spectra at 303 K (Fig. 1). Note that the unit is eV except for the high-frequency dielectric constant $\varepsilon_{\infty}$, which is dimensionless. The 90% reliability of the fitting parameters is given in parentheses.

<table>
<thead>
<tr>
<th>xPT</th>
<th>$\varepsilon_{\infty}$</th>
<th>$A_1$</th>
<th>$E_{p1}$</th>
<th>$\Gamma_1$</th>
<th>$E_{i1}$</th>
<th>$A_2$</th>
<th>$E_{p2}$</th>
<th>$\Gamma_2$</th>
<th>$E_{i2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.29</td>
<td>3.64 (0.03)</td>
<td>129 (35)</td>
<td>3.61 (0.07)</td>
<td>0.89 (0.07)</td>
<td>3.39 (0.03)</td>
<td>139 (7)</td>
<td>4.74 (0.02)</td>
<td>1.91 (0.05)</td>
<td>3.49 (0.04)</td>
</tr>
<tr>
<td>0.31</td>
<td>4.22 (0.04)</td>
<td>149 (117)</td>
<td>3.45 (0.21)</td>
<td>0.73 (0.22)</td>
<td>3.45 (0.15)</td>
<td>81 (12)</td>
<td>4.79 (0.04)</td>
<td>1.95 (0.07)</td>
<td>3.28 (0.07)</td>
</tr>
<tr>
<td>0.33</td>
<td>3.99 (0.04)</td>
<td>150 (99)</td>
<td>3.46 (0.17)</td>
<td>0.73 (0.17)</td>
<td>3.46 (0.22)</td>
<td>89 (10)</td>
<td>4.81 (0.03)</td>
<td>2.02 (0.05)</td>
<td>3.26 (0.06)</td>
</tr>
<tr>
<td>0.35</td>
<td>4.07 (0.08)</td>
<td>154 (142)</td>
<td>3.41 (0.30)</td>
<td>0.86 (0.28)</td>
<td>3.41 (0.25)</td>
<td>91 (21)</td>
<td>4.74 (0.05)</td>
<td>1.93 (0.09)</td>
<td>3.32 (0.11)</td>
</tr>
</tbody>
</table>
The absorption edges of the PIN-PMN-PT crystals show

\[ \frac{E_p}{C_0} = \frac{1}{E_{\infty}} + 2P \frac{a_2(E)}{c - \frac{E}{E_2}} \]

where \( E_{\infty} \) is the high-frequency dielectric constant, \( P \) is the Cauchy principal part of the integral, \( E \) is the incident photon energy, \( A_j, E_{p_j}, \Gamma_j, \) and \( E_{o_j} \) are the amplitude, peak position energy, broadening term, and Tauc gap energy of the \( j \)th oscillator, respectively. The above DTL model abides by the Kramers-Kröning transformation in the entirely measured photon energy region, which is applied to semiconductor and dielectric materials.\(^{14,15,22}\) At near-normal incidence, the dielectric functions are related to the reflectance \( R \) by the Fresnel formula:

\[ R = \frac{1}{\left( \sqrt{\varepsilon(E) - 1} / \sqrt{\varepsilon(E) + 1} \right)^2} \]

The best-fit parameter values of the model (i.e., dielectric functions) can be obtained as shown in Figs. 1(c)–1(f).

Figs. 3(a) and 3(b) depict the real and imaginary parts of the complex dielectric functions from the DTL dispersion model. Parameter values of the DTL dispersion model are listed in Table I. The optical structures shown in the \( \varepsilon \) spectrum are described by the charge-transfer transitions or the interband transitions.\(^{5,3}\) The charge transfer mainly occurs between the Pb 6p, Ti 3d, and O 2p orbitals during the ferroelectric-paraelectric phase transition. The Pb-O bonding strongly affects the Pb 6p-Ti 3d hybridization in the TiO\(_6\) octahedron.\(^{24}\) Moreover, all the \( \Gamma_1 < \Gamma_2 \) shown in Table I indicates that the broadening term of the first oscillator is smaller than that of the second oscillation. To explain the temperature

![FIG. 2. (a) Transmittance spectra of PIN-PMN-0.31PT crystal at the temperatures of 303 K, 333 K, 363 K, 393 K, 423 K, and 453 K, respectively. The inset shows an enlarged transmittance spectra in the fundamental bandgap region of 3–3.3 eV. Transmittance spectra of (b) PIN-PMN-0.33PT and (c) PIN-PMN-0.35PT crystals at the temperatures of 303 K and 453 K, respectively. Note that the horizontal direction in (b) and (c) is logarithmic coordinate for clarity. (d) AFM surface morphology of PIN-PMN-PT crystals.](image)

bottom of the O \( p \) bands, reflecting the main crystal field splitting of the O 2p bands into \( p_x \) (one per O) and \( p_y \) (two per O) because of hybridization with Nb. The primary Nb-O hybridization is \( e_g - p_d \) and Pb \( p-O \) hybridization is not the strongest interaction for the purpose of the O crystal field.\(^{18}\) The lower valence band for PT consists of two orbitals; one is the Pb 5d orbitals on the high energy side and the other is the O 2s orbitals on the low energy. The upper valence band of simple perovskite-type oxides ABO\(_3\) consists of the O 2p orbitals mixed with the \( d \) valence electrons of the B atom.\(^{19}\) The conduction band consists of the \( t_{2g} \) and \( e_g \) bands of Ti 3d orbital, above which is the Pb 6p band. It was reported that the shape of the upper valence band for several Pb-based perovskite-type oxides ABO\(_3\) only changes slightly despite B site substitution while those of the conduction band are remarkably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notably modified by the variation of the B site substitution while those of the conduction band are notable

\[ E_D = \frac{1}{C_0} \sum_{j=1}^{2} \frac{A_j E_j}{(E - E_j)^2 + \Gamma_j^2} \]

where \( A_j \) and \( \Gamma_j \) are the amplitude and broadening term, respectively. The above model can be obtained as shown in Figs. 1(c)–1(f).

Figs. 3(a) and 3(b) depict real and imaginary parts of the complex dielectric functions from the DTL dispersion model. Parameter values of the model are listed in Table I. The optical structures shown in the \( \varepsilon \) spectrum are described by the charge-transfer transitions or the interband transitions.\(^{5,3}\) The charge transfer mainly occurs between the Pb 6p, Ti 3d, and O 2p orbitals during the ferroelectric-paraelectric phase transition. The Pb-O bonding strongly affects the Pb 6p-Ti 3d hybridization in the TiO\(_6\) octahedron.\(^{24}\) Moreover, all the \( \Gamma_1 < \Gamma_2 \) shown in Table I indicates that the broadening term of the first oscillator is smaller than that of the second oscillation. To explain the temperature

\[ Transmittance = \frac{1}{1 + \sqrt{\frac{C_0}{E}}(E - E_{\infty})^{1/2}} \]

where \( C_0 \) is the high-frequency dielectric constant, \( A_j \) and \( \Gamma_j \) are the amplitude and broadening term, respectively. The above model can be obtained as shown in Figs. 1(c)–1(f).

Figs. 3(a) and 3(b) depict real and imaginary parts of the complex dielectric functions from the DTL dispersion model. Parameter values of the model are listed in Table I. The optical structures shown in the \( \varepsilon \) spectrum are described by the charge-transfer transitions or the interband transitions.\(^{5,3}\) The charge transfer mainly occurs between the Pb 6p, Ti 3d, and O 2p orbitals during the ferroelectric-paraelectric phase transition. The Pb-O bonding strongly affects the Pb 6p-Ti 3d hybridization in the TiO\(_6\) octahedron.\(^{24}\) Moreover, all the \( \Gamma_1 < \Gamma_2 \) shown in Table I indicates that the broadening term of the first oscillator is smaller than that of the second oscillation. To explain the temperature

\[ \frac{E_p}{C_0} = \frac{1}{E_{\infty}} + 2P \frac{a_2(E)}{c - \frac{E}{E_2}} \]

where \( E_{\infty} \) is the high-frequency dielectric constant, \( P \) is the Cauchy principal part of the integral, \( E \) is the incident photon energy, \( A_j \), \( E_{p_j} \), \( \Gamma_j \), and \( E_{o_j} \) are the amplitude, peak position energy, broadening term, and Tauc gap energy of the \( j \)th oscillator, respectively. The above model can be obtained as shown in Figs. 1(c)–1(f).

Figs. 3(a) and 3(b) depict real and imaginary parts of the complex dielectric functions from the DTL dispersion model. Parameter values of the model are listed in Table I. The optical structures shown in the \( \varepsilon \) spectrum are described by the charge-transfer transitions or the interband transitions.\(^{5,3}\) The charge transfer mainly occurs between the Pb 6p, Ti 3d, and O 2p orbitals during the ferroelectric-paraelectric phase transition. The Pb-O bonding strongly affects the Pb 6p-Ti 3d hybridization in the TiO\(_6\) octahedron.\(^{24}\) Moreover, all the \( \Gamma_1 < \Gamma_2 \) shown in Table I indicates that the broadening term of the first oscillator is smaller than that of the second oscillation. To explain the temperature

\[ Transmittance = \frac{1}{1 + \sqrt{\frac{C_0}{E}}(E - E_{\infty})^{1/2}} \]

where \( C_0 \) is the high-frequency dielectric constant, \( A_j \) and \( \Gamma_j \) are the amplitude and broadening term, respectively. The above model can be obtained as shown in Figs. 1(c)–1(f).

Figs. 3(a) and 3(b) depict real and imaginary parts of the complex dielectric functions from the DTL dispersion model. Parameter values of the model are listed in Table I. The optical structures shown in the \( \varepsilon \) spectrum are described by the charge-transfer transitions or the interband transitions.\(^{5,3}\) The charge transfer mainly occurs between the Pb 6p, Ti 3d, and O 2p orbitals during the ferroelectric-paraelectric phase transition. The Pb-O bonding strongly affects the Pb 6p-Ti 3d hybridization in the TiO\(_6\) octahedron.\(^{24}\) Moreover, all the \( \Gamma_1 < \Gamma_2 \) shown in Table I indicates that the broadening term of the first oscillator is smaller than that of the second oscillation. To explain the temperature
dependence, the OBG energies for PIN-PMN-PT crystals are calculated by considering a direct transition between the valence and conduction bands. Direct transition is a first-order process because no phonon is involved. The absorption coefficient $x$ as a function of photon energy is expressed by the Tauc relation: $x(hv) \propto (hv - E_g)^{1/2}$, where $v$ is the frequency, $h$ is the Planck constant, and $E_g$ is the allowed direct OBG energy. Therefore, the straight line between $(xh)^2$ and $hv$ will provide the OBG value, which is extrapolated by the linear portion of the plot to $(xh) = 0$, as shown in Figs. 3(c)–3(f). At 303 K, the direct bandgap $E_g$ of PIN-PMN-0.29PT, PIN-PMN-0.31PT, PIN-PMN-0.33PT, and PIN-PMN-0.35PT crystals are $3.18 \pm 0.02$, $3.18 \pm 0.02$, $3.17 \pm 0.02$, and $3.17 \pm 0.02$ eV, showing a redshift trend with increasing PT concentration. Similar phenomena are also reported in relaxor PbZn$_{1/3}$Nb$_{2/3}$O$_3$-PbTiO$_3$ (PZN-PT). The basic energy levels are derived from the common $(Bi_2B_3)O_6$ oxygen octahedral structure in $ABO_3$-type perovskite ferroelectrics. Thus, similar optical absorption edges with slight differences are found in PIN-PMN-PT and PZN-PT crystals due to different B-site cations and concentration. Temperature dependence of the critical point energies is displayed in Fig. 4. An empirical formula for the bandgap energy of each octahedron and A cations being centrally located in the $A_0_1_2$ cuboctahedral cavity formed by eight octahedra. The tetragonal and rhombohedral phases might coexist and various low-symmetry phases have been postulated in the MPB region, indicating a complicated chemical structure of PMN-PT based solid solutions. Synchrotron x-ray powder diffraction measurements reveal that the orthorhombic or monoclinic phase of $M_c$ type with space group $Pm$ coexist with either rhombohedral or tetragonal phase in the MPB and their volume fractions changes with increasing temperature. Temperature dependent dielectric constant, piezoelectric resonance frequency and powder neutron diffraction studies suggest a $M_b$ type with space group $Cm$ existing in PT poor region of MPB. The short range $M_b$ type monoclinic order at RT can grow to long range monoclinic order on lowering the temperature. Moreover, three intermediate phases including one orthorhombic phase and two monoclinic phases are proposed to separate the tetragonal and rhombohedral phase. Such low symmetry phases were even observed in a wide PT concentration range of 0.3–0.47. The phase transition between two monoclinic phases is of first order and shows a large thermal hysteresis. A similar competing mechanism between rhombohedral and monoclinic order is reported in PZT crystal near MPB region as well. The complex MPB states of the PMN-PT/PIN-PMN-PT systems point to an energy balance between different phases, which is much more delicate than that of PZT based system.

In conclusion, we have investigated optical properties and electronic band structures of (001)-face PMN-PT single crystals around MPB region by transmittance and reflectance spectra from 303 to 453 K. Three typical interband transitions and dielectric functions are correlated with structural changes from rhombohedral to tetragonal phase. Deviation from the linear behaviors of critical point energies $E_a$ and $E_b$...
versus PT concentration can be observed, indicating that the variation of electronic band structures are closely related to the phase transitions.

This work was financially supported by Major State Basic Research Development Program of China (Grant Nos. 2011CB922200 and 2013CB922300), Natural Science Foundation of China (Grant Nos. 11374097 and 61376129), Projects of Science and Technology Commission of Shanghai Municipality (Grant Nos. 13JC1402100 and 13JC1404200), and the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning.

6Z. G. Ye, MRS Bull. 34, 277 (2009).