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Combined effect of the transition layer and interfacial coupling on the properties of ferroelectric bilayer film

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Within the framework of modified Ginzburg–Landau–Devonshire phenomenological theory, a ferroelectric bilayer film with a transition layer within each constituent film and an interfacial coupling between two materials has been studied. Properties including the Curie temperature and the spontaneous polarization of a bilayer film composed of two equally thick ferroelectric constituent films are discussed. The results show that the combined effect of the transition layer and the interfacial coupling plays an important role in explaining the interesting behaviour of ferroelectric multilayer structures consisting of two ferroelectric materials.

Keywords: ferroelectric bilayer film, spontaneous polarization, Curie temperature, phase transition
PACC: 7755, 7730, 7780B

1. Introduction

Artificial bilayer, multilayer films, or superlattice structures have attracted much attention in recent materials research because of their promising properties and new various applications.[1−7] Their properties include improvable remnant polarization, large dielectric response, low dielectric loss and high electrical breakdown fields, which differ dramatically from those of the single film.[8−12] These properties, for example, the dielectric constant of the samples, could not be explained by a simple series connection of the component slabs[13] and was obviously dependent on the component slab thickness.[14] Many authors think that these phenomena originate from the interfacial coupling or interaction between dipoles in two materials, which implies that the interfacial coupling may play a crucial role in ferroelectric multilayer structures. Hence, much effort was devoted to analysing the effects of the interfacial coupling on the characters of ferroelectric bilayer films or superlattices both experimentally and theoretically and lots of interesting results have been obtained.

Experimentally, a double hysteresis loop has been observed by Wu *et al*[15] in a $(Pb_{0.90}La_{0.10})Ti_{0.975}O_3$ /$Pb(Zr_{0.20}Ti_{0.80})O_3$ bilayer thin film fabricated by using radio frequency magnetron sputtering with a PbO_x buffer layer. They thought that the double loop behaviour should be attributed to the competition among the intrinsic ferroelectric coupling in the ferroelectrics and the antiferroelectric coupling among the dipoles at the interface. Ranjith *et al*[16] observed polarization hysteresis and capacitance–voltage characteristics of $Pb(Mg_{1/3}Nb_{2/3})O_3$ (PMN)–$PbTiO_3$ (PT) bilayer films deposited through pulsed laser ablation deposition. The size dependent ferroelectric and antiferroelectric characteristics were obviously shown. Recently, Sim *et al*[17] reported on an anomalous polarization enhancement in a Pb $(Zr_{0.52}Ti_{0.48})$ O_3 (PZT) /$(Bi_{3.15}Nd_{0.85})$ Ti_3O_{12}(BNT) bilayer thin film which was fabricated via a synthesis route of combining sol-gel and rf sputtering. They also found an obvious improvement in fatigue behaviour in a BNT/PZT bilayer thin film as compared with that of the single layer PZT film. In theory, two major approaches have been used to discuss the above behaviours: one is within the framework of transverse Ising model (TIM);[18−20] the other one is based on the Landau–Ginzburg model.[21−23] According to the TIM, Qu *et al*[18] investigated the ferroelectric superlattice with a first-order phase transition by using the experimental data of $BaTiO_3/PbTiO_3$ superlattice. It is shown that when the strength of interfacial coupling is weak, a size-driven phase transition occurs in the superlattice and *vice versa*. The multiple hysteresis loop behaviour of a ferroelectric bilayer film with an antiferroelectric interfacial coupling on the basis of the TIM has been explained.[20] Within the framework of Landau phe-

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nomenological theory, Chew *et al*[21] presented that there was an antiferroelectric interfacial coupling in the ferroelectric bilayer film or superlattice structure, by analogy with the antimagnetic interfacial coupling in the Fe/Cr/Fe multilayer film. It was revealed that the hysteresis loop patterns varied between typically ferroelectric and typically antiferroelectric depending on the layer thickness and the magnitude of the interfacial coupling constant. Based on the idea of Chew *et al*, the hysteresis loop and the size effect of the ferroelectric bilayer film have been illustrated by considering the spatial variation of polarization and the surface effect.[23] Other results have also been reported. Essaoudi1 *et al*[24] applied the effective field, with using a probability distribution technique, to the study of the effects of the interface coupling and the thickness on the hysteresis, susceptibility and pyroelectric coefficient of the bilayer film. Using the first-principles density-functional theory in the local density approximation, Neaton and Rabe[25] studied the spontaneous polarization of epitaxial $BaTiO_3/SrTiO_3$ superlattice and reported that the obvious polarization enhancement could be achieved in perovskite oxide superlattices.

However, in the above theoretical studies, a sudden structure transition from surface to interior for each constituent film is assumed, which is not realistic because the transition of structure should take place gradually, therefore, the transition layer should exist within each constituent film. It provides a continuous link between two constituent films and so the structure should vary smoothly. The transition layer was introduced first by Lü and Cao[26] to study the effect of the gradual transition of structure on the properties of a ferroelectric thin film clamped between two electrodes. We further consider that the effect of the surface or interface transition layers should be taken into account for a ferroelectric bilayer film or superlattice design. The combined effect of the interfacial coupling and the transition layer should be investigated. Up to now, we have not found the reports on the combined effect of the transition layer and the interfacial coupling on properties of the ferroelectric bilayer film.

In the present paper, using the modified Ginzburg–Landau–Devonshire (GLD) method, we present a theoretical study on the combined effect of the transition layer and the interfacial coupling on Curie temperature and spontaneous polarization of the ferroelectric bilayer film composed of two equally thick ferroelectric constituent films.

2. The model

The configuration of a ferroelectric bilayer film composed of materials 1 and 2 of layer thickness L_1 and L_2, respectively, and the transition layers, clamped between two electrodes, is sketched in Fig.1. We assume that the layer 1 and layer 2 are of monodomain, the directions of the polarizations P_1 in layer 1 and P_2 in layer 2 are normal to the film surface and along the positive direction of the z-axis. The properties of the film are homogeneous in a plane parallel to the surface of the film and the variation occurs only along the film thickness.

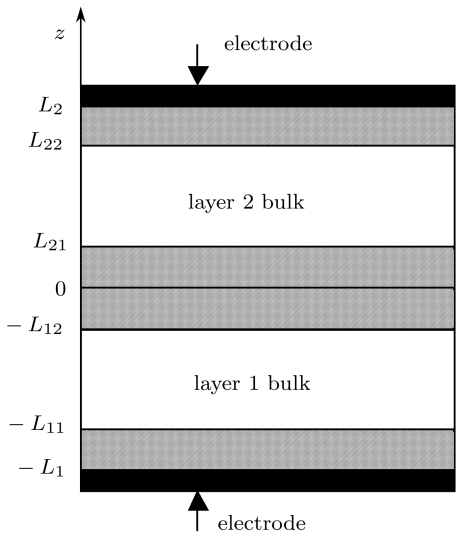


Fig.1. Geometric structure of a bilayer film under study.

To study this bilayer film system with the interfacial coupling originating from the interaction between the dipoles in two constituent thin films, a modified GLD free energy for each constituent thin film needs establishing. According to Ref.[26], we introduce a second power of polarization in the GLD free energy and assume its coefficient to be a function of position in order to reflect the contribution of the transition layers for each slab. Considering a second order phase transition system, the total free energy of a ferroelectric bilayer film per unit area can be expressed as

$$G = G_1 + G_2 + G_{\text{int}}, \tag{1}$$

where G_1, G_2 and G_{int} represent the free energy densities of layer 1, layer 2 and the interfacial layer, respectively, the expression for G_1 is given as

$$G_1 = \int_{-L_1}^{0} \mathrm{d}z \left\{ \frac{1}{2} A_1 \left[T - T_{01} \right] P_1^2 + \frac{1}{2} B_1 \psi_1(z) P_1^2 + \frac{1}{4} C_1 P_1^4 + \frac{1}{2} K_1 \left(\frac{\mathrm{d}P_1}{\mathrm{d}z} \right)^2 - E_1 P_1 \right\} \tag{2}$$

with coefficients A_1, B_1, C_1, and K_1 being positive and independent of both temperature T and position z, T_{01} the transition temperature of the bulky ferroelectric of layer 1, and E_1 the local electric field. The function $\psi_1(z)$ in expression (2) reflects the transition layer effect. In order to ensure the continuity of $P_1(z)$ and its derivative, we require $\psi_1(-L_{11}) = \psi_1(-L_{12}) = 0$ and $(\mathrm{d}\psi_1/\mathrm{d}z)_{z=-L_{11}} = (\mathrm{d}\psi_1/\mathrm{d}z)_{z=-L_{12}} = 0$, where $-L_{11}(-L_{12})$ is the boundary position of lower (upper) transition layer in layer 1 (see Fig.1). Similarly, the free energy density of layer 2 can be expressed as

$$G_2 = \int_{0}^{L_2} \mathrm{d}z \left\{ \frac{1}{2} A_2 \left[T - T_{02} \right] P_2^2 + \frac{1}{2} B_2 \psi_2(z) P_2^2 + \frac{1}{4} C_2 P_2^4 + \frac{1}{2} K_2 \left(\frac{\mathrm{d}P_2}{\mathrm{d}z} \right)^2 - E_2 P_2 \right\}. \tag{3}$$

The free energy of the interfacial layer is given as follows:

$$G_{\mathrm{int}} = -J P_1(0) P_2(0), \tag{4}$$

where $P_1(0)$ and $P_2(0)$ are the spontaneous polarizations at $z = 0$ in layer 1 and layer 2, respectively, J is the interfacial coupling constant. In the case of ferroelectric coupling, we take $J > 0$.

To concentrate on the effects produced by the interfacial coupling and the transition layer, a convenient assumption is made that materials 1 and 2 have the same phenomenological parameters, i.e. $T_{01} = T_{02} = T_0$, $A_1 = A_2 = A$, $B_1 = B_2 = B$, $C_1 = C_2 = C$, and $K_1 = K_2 = K$. Moreover, since we choose two equally thick materials and calculate the mean polarization of the bilayer film system, the depolarization field can be neglected, thus, $E_1 = E_2 = E$, where E is the uniform external electric field.[23]

When the system is in an equilibrium state, $\delta G = 0$ (with respect to variations of P_1 and P_2). We can obtain the following Euler–Lagrange equations:

$$K \frac{\mathrm{d}^2 P_1}{\mathrm{d}z^2} = A \left[T - T_0 \right] P_1 + B \psi_1(z) P_1 + C P_1^3 - E, \tag{5a}$$

$$K \frac{\mathrm{d}^2 P_2}{\mathrm{d}z^2} = A \left[T - T_0 \right] P_2 + B \psi_2(z) P_2 + C P_2^3 - E \tag{5b}$$

with the corresponding boundary conditions:

$$\left(\frac{\mathrm{d}P_1}{\mathrm{d}z} \right) = 0 \qquad (z = -L_1), \tag{6}$$

$$K \left(\frac{\mathrm{d}P_1}{\mathrm{d}z} \right) = J P_2 \qquad (z = 0), \tag{7}$$

$$K \left(\frac{\mathrm{d}P_2}{\mathrm{d}z} \right) = -J P_1 \qquad (z = 0), \tag{8}$$

$$\left(\frac{\mathrm{d}P_2}{\mathrm{d}z} \right) = 0 \qquad (z = L_2). \tag{9}$$

It is convenient to rescale the variables into dimensionless forms. We set $t = T/T_0$, $f_i = P_i/P_0$ $(i = 1, 2)$ with $P_0 = \sqrt{AT_0/C}$, $e = E/E_0$ with $E_0 = P_0/\varepsilon_0$, $\zeta = z/\xi_0$ with $\xi_0 = \sqrt{K/AT_0}$, $\eta = B/B_0$ with $B_0 = AT_0$, $j = J/\xi_0 AT_0$, $l_i = L_i/\xi_0$ $(i = 1, 2)$, $\sigma = (\varepsilon_0 AT_0)^{-1}$, where ε_0 is the dielectric constant of vacuum. Finally, we can obtain the following equations:

$$\frac{\mathrm{d}^2 f_1}{\mathrm{d}\zeta^2} = \left[t - 1.0 \right] f_1 + \eta \psi_1(\zeta) f_1 + f_1^3 - \sigma e, \tag{10a}$$

$$\frac{\mathrm{d}^2 f_2}{\mathrm{d}\zeta^2} = \left[t - 1.0 \right] f_2 + \eta \psi_2(\zeta) f_2 + f_2^3 - \sigma e. \tag{10b}$$

The corresponding boundary conditions become

$$\frac{\mathrm{d}f_1}{\mathrm{d}\zeta} = 0 \qquad (\zeta = -l_1), \tag{11}$$

$$\frac{\mathrm{d}f_1}{\mathrm{d}\zeta} = j f_2 \qquad (\zeta = 0), \tag{12}$$

$$\frac{\mathrm{d}f_2}{\mathrm{d}\zeta} = -j f_1 \qquad (\zeta = 0), \tag{13}$$

$$\frac{\mathrm{d}f_2}{\mathrm{d}\zeta} = 0 \qquad (\zeta = l_2). \tag{14}$$

Parameter σ is the ratio of the Curie constant to Curie temperature of the bulky material. Considering a real material with a second-order phase transition

(the Curie constant is about 10^3 and the Curie temperature is about 10^2 K) we take $\sigma = 6$ as a representative value.

Since experimental data on the effects of the transition layer are unavailable, two simple forms are chosen as the distribution functions $\psi_1(\zeta)$ and $\psi_2(\zeta)$. These peculiar choices of $\psi_1(\zeta)$ and $\psi_2(\zeta)$, shown below, do not affect the generality of the results and conclusions:

$$\psi_1(\zeta) = \begin{cases} \dfrac{(\zeta + l_{11})^2}{\lambda_{11}^2} & -l_1 \le \zeta \le -l_{11}, \\ 0 & -l_{11} \le \zeta \le -l_{12}, \\ \dfrac{(\zeta + l_{12})^2}{\lambda_{12}^2} & -l_{12} \le \zeta \le 0, \end{cases} \tag{15}$$

$$\psi_2(\zeta) = \begin{cases} \dfrac{(\zeta - l_{21})^2}{\lambda_{21}^2} & 0 \le \zeta \le l_{21}, \\ 0 & l_{21} \le \zeta \le l_{22}, \\ \dfrac{(\zeta - l_{22})^2}{\lambda_{22}^2} & l_{22} \le \zeta \le l_2, \end{cases} \tag{16}$$

where $l_{1i} = L_{1i}/\xi_0$, $l_{2i} = L_{2i}/\xi_0$, $(i = 1, 2)$, parameter $\lambda_{11}(\lambda_{12})$ reflects the variation in intensity of the free energy density near lower (upper) surface in layer 1, and the physical meaning of $\lambda_{21}(\lambda_{22})$ in layer 2 is the same as that of $\lambda_{11}(\lambda_{12})$. For simplicity, the two transition layers in each slab are assumed to be symmetric, i.e. $\lambda = \lambda_{11} = \lambda_{12} = \lambda_{21} = \lambda_{22}$ and $(l_1 - l_{11}) = l_{12} = l_{21} = (l_2 - l_{22})$. Define $l_s = 2(l_1 - l_{11}) = 2l_{12} = 2l_{21} = 2(l_2 - l_{22})$, which represents the thickness of the transition layer for each slab. The mean spontaneous polarization $\bar{f}$ is defined as the following formula:

$$\bar{f} = \frac{1}{l}\left[\int_{-l_1}^{0} f_1 \mathrm{d}\zeta + \int_{0}^{l_2} f_2 \mathrm{d}\zeta\right], \tag{17}$$

where $l = l_1 + l_2$ is the thickness of bilayer film.

3. Results and discussion

The curves for the values of average spontaneous polarization of a bilayer film $\bar{f}$ versus coupling constant j for different values of λ and thickness of the transition layer of each slab l_s are shown in Fig.2. From Fig.2 we can see that the average spontaneous polarization $\bar{f}$ is enhanced with the strength of interfacial coupling j increasing for the same transition layer. It is indicated that the increase of the interfacial coupling j will favour the bilayer film in ferroelectric phase when the bilayer film is composed of two materials with identical phenomenological parameters and thicknesses. As λ reduces or l_s increases, the curves of the average spontaneous polarization $\bar{f}$ versus coupling constant j drop obviously. When $j = 0$, that is, in the case of the series connection of two capacitors, the average spontaneous polarization $\bar{f}$ decreases notably with the value of λ reducing or the value of l_s increasing, which comes only from the effect of the transition layer. The case is similar to that of Ref.[26]. The results show that the interfacial coupling j favours the system in ferroelectric phase, but the transition layer which suppresses the polarization is a disadvantage to the stabilization of ferroelectric phase for a system. The competition between the transition layer and the interfacial coupling can give rise to many unusual phenomena discussed below in detail.

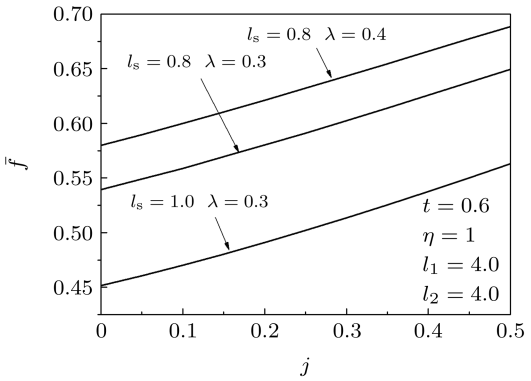


Fig.2. Curves for coupling constant j dependences of the average spontaneous polarization $\bar{f}$ of bilayer films with different values of l_s and λ.

The curves for average spontaneous polarization $\bar{f}$ of a bilayer film against interfacial coupling constant j, l_s and λ, respectively, for different thicknesses of film are given in Fig.3. In Fig.3(a), the values of l_s and λ are fixed. We can see that the three curves for the different thicknesses of the bilayer film intersect at one point, which is located at $j = 0.415$. When $j < 0.415$, i.e. the interfacial coupling is weak, the effect of the transition layer is dominant, so the polarization decreases with the thickness of the bilayer film decreasing for the same j. The weaker the interfacial coupling j (j can be zero) is, the more greatly the value of the polarization will lower, when the thickness of the bilayer film decreases. If $j > 0.415$, i.e. the interfacial coupling is strong and predominates over the system, the polarization augments with the thickness of the bilayer film decreasing, which also means that the size-driven phase transition cannot occur. According to Fig.2, the interfacial coupling favours the system in

ferroelectric phase, whereas the transition layer suppresses the ferroelectric phase of the system, so that there should be a transition point, which is ascribed to the competition between the transition layer and the interfacial coupling. The anomalous behaviour of the polarization was observed to increase with the decrease of the thickness of the bilayer film in the $BaTiO_3$ (BT)/$SrTiO_3$ (ST) superlattice by Shimuta *et al*,[11] which is also consistent with the theoretical results obtained by Neaton and Rabe[25] by using first-principles. In Fig.3(b), we fix $j = 0.1$ and $\lambda = 0.3$. It can be clearly seen that the polarization decreases with the value of l_s increasing for the same thickness of the bilayer film and finally the polarization drops to zero at a certain value of l_s. This distinctly shows that the existence of the transition layer makes the system unfavourable for the occurrence of ferroelectric phase. The three curves with different thicknesses of the bilayer films intersect at a transition point, where $l_s = 0.484$. If $l_s > 0.484$, the polarization reduces as the thickness of the bilayer film decreases; when $l_s < 0.484$, the polarization is enhanced with the thickness of the bilayer film decreasing, the size-driven phase transition cannot emerge. From Fig.3(c), we take $j = 0.1$ and $l_s = 0.8$. One can see that the polarization decreases with the value of λ decreasing for the same thickness of the bilayer film, and in the end the polarization drops to zero at a certain value of λ. There is also a transition point where the value of λ is about 0.658. If $\lambda < 0.658$, the polarization decreases with the reduction of the thickness of the bilayer film for the same λ; if $\lambda > 0.658$, the polarization augments as the thickness of the bilayer film decreases, the size-driven phase transition still cannot appear. From the analysis of Fig.3, one can find that the physical reason for the above abnormal phenomena is the existence of the interfacial coupling between two layers and structure transition layer. If the effect of the interfacial coupling is stronger than that of the transition layer, the polarization will increase with the thickness of the bilayer film reducing. However, if the effect of the interfacial coupling is less than that of the transition layer, the polarization will decrease with the reduction of the thickness of the bilayer film, thus the size-driven phase transition may take place.

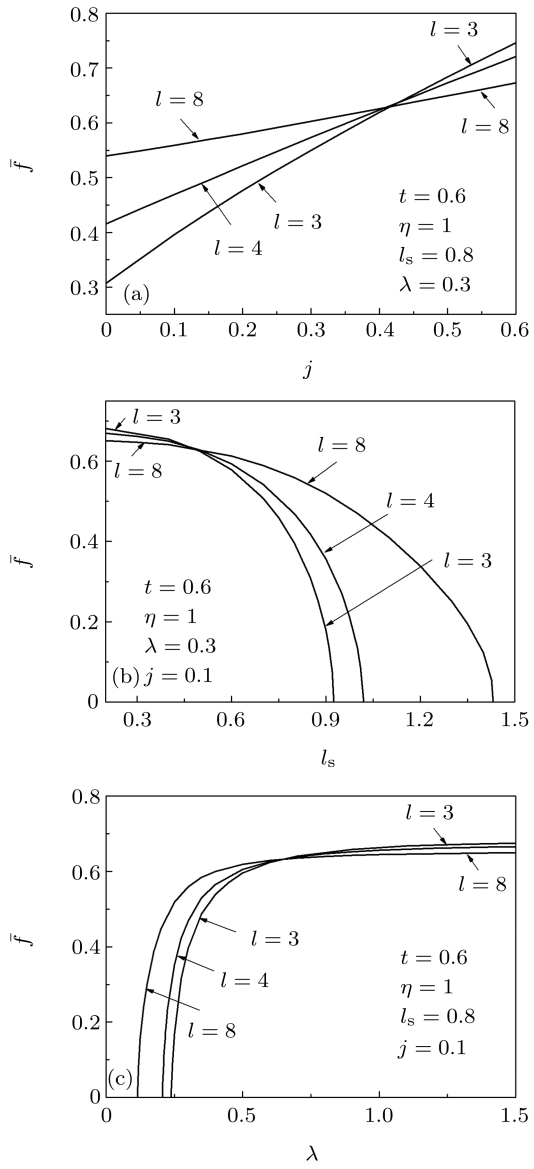


Fig.3. Curves for the values of average spontaneous polarization $\bar{f}$ versus the interfacial coupling constant j (a), l_s (b) and λ (c) for bilayer films with different thicknesses.

Figure 4 shows the curves for temperature dependences of the average spontaneous polarization of bilayer films for different values of interfacial coupling j, with the values of λ and l_s fixed. The four groups of curves in Fig.4 show a general trend: the increase of temperature leads the ferroelectric–paraelectric phase transition to occur and the average spontaneous polarization to drop to zero at a phase transition temperature, which is the characteristic feature of second-order phase transition. One can see that as the coupling j increases, the Curie temperature and the amplitude of the spontaneous polarization of the bilayer film increase. When $j = 0$, the Curie temperature of the bilayer film is always smaller than that of the bulky material, which comes only from the effect of the transition layers. However, an interesting behaviour happens when the coupling j is large enough so that the Curie temperature of the bilayer film is higher than

that of the bulky material. From the analysis of Fig.2 and Ref.[26], we can infer that the Curie temperature and the amplitude of the spontaneous polarization of the bilayer film decrease with the value of l_s increasing or the value of λ reducing for a given coupling constant.

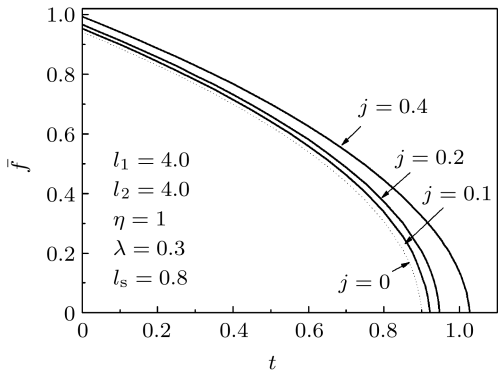


Fig.4. Curves for the values of average spontaneous polarization $\bar{f}$ versus temperature t of bilayer films with different values of interfacial coupling constant j.

The curves for Curie temperature of a bilayer film against interfacial coupling constant j, l_s and λ, respectively, for different thicknesses are shown in Fig.5. In Fig.5(a), where l_s and λ are fixed, one can see that the Curie temperature of the bilayer film is enhanced with the increase of the interfacial coupling j for the same thickness of the bilayer film. Three curves for the different thicknesses of the bilayer film intersect at one point, where $j = 0.452$, which is a transition point. When $j < 0.452$, the Curie temperature of the bilayer film reduces as the thickness of a bilayer film decreases for a given interfacial coupling j; if $j > 0.452$, the Curie temperature of the bilayer film augments with the reduction of the thickness of film, and the size-driven phase transition cannot take place. The physical reason is the same as that of Fig.3(a). The curves for Curie temperatures of the bilayer film versus the two parameters of the transition layer, l_s and λ, are elucidated in Figs.5(b) and 5(c), respectively, with taking the interfacial coupling $j = 0.2$. We can also see that Figs.5(b) and 5(c) each show a transition point where the value of l_s is about 0.614 and the value of λ is about 0.441. If $l_s > 0.614$ or $\lambda < 0.441$, the Curie temperature of the bilayer film reduces with the thickness of film decreasing; when $l_s < 0.614$ or $\lambda > 0.441$, the Curie temperature of the bilayer film is enhanced as the thickness of film reduces, that means that the size-driven phase transition cannot take place. The results show that when the effect of the interfacial coupling is less than that of the transition layer, the Curie temperature of the bilayer film reduces as the thickness of film decreases. On the contrary, the Curie temperature of the bilayer film increases as the thickness of film decreases, and the size-driven phase transition cannot happen.

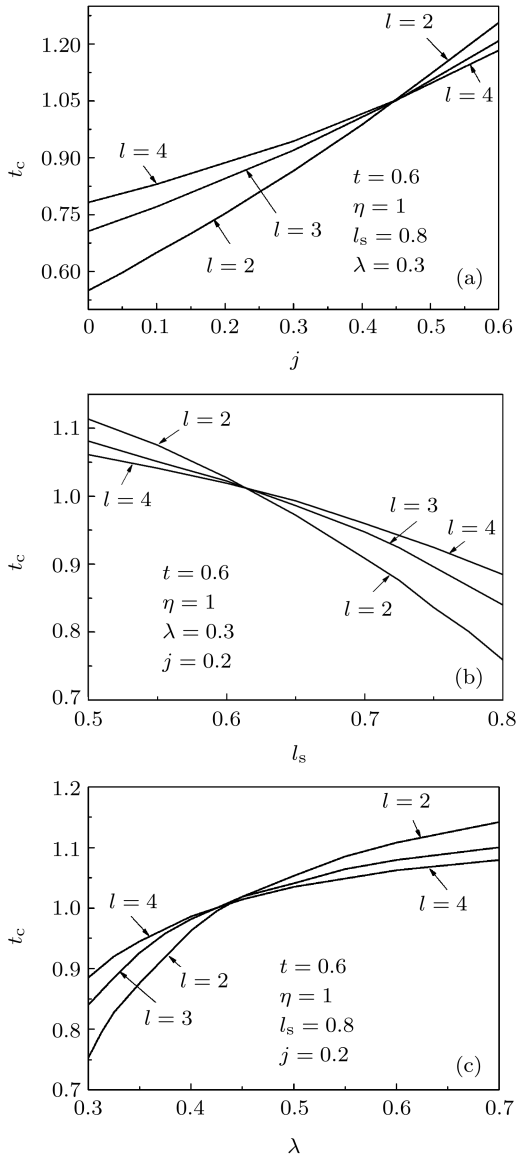


Fig.5. Curves for Curie temperatures versus interfacial coupling constant j (a), l_s (b) and λ (c) for bilayer films with different thicknesses.

4. Conclusions

The combined effect of the transition layer and the interfacial coupling on the Curie temperature and the spontaneous polarization of a ferroelectric bilayer film is investigated by means of the modified GLD theory. The following results are obtained: (i) the effects of both the transition layer and the interfa-

cial coupling on the properties of ferroelectric bilayer film must be considered; (ii) the interfacial ferroelectric coupling (in our paper $j > 0$) favours the ferroelectric state for the system, while the effect of the transition layer is to suppress the system in the ferroelectric phase; (ii) there may be a transition point due to the competition between the transition layer and the interfacial coupling, and if the effect of the interfacial coupling is less than that of the transition layer, the size-driven phase transition may take place; on the contrary, the size-driven phase transition cannot occur; (iv) the unusual behaviours of the Curie temperature and the spontaneous polarization of a ferroelectric bilayer film depend on the competition between the transition layer and the interfacial coupling.

References

[1] Guigues B, Guillan J, Defaÿ E, Garrec P, Wolozan D, André B, Laugier F, Pantel R, Gagnard X and Aïd M 2007 *J. Eur. Ceram. Soc.* **27** 3851

[2] Dawber M, Lichtensteiger C, Cantoni M, Veithen M, Ghosez P, Johnston K, Rabe K M and Triscone J M 2005 *Phys. Rev. Lett.* **95** 177601

[3] Wu J G, Xiao D Q, Zhu J G, Zhu J L, Tan J Z and Zhang Q L 2007 *Appl. Phys. Lett.* **90** 082902

[4] Stephanovich V A, Lukyanchuk I A and Karkut M G 2005 *Phys. Rev. Lett.* **94** 047601

[5] Ranjith R and Krupanidhi S B 2007 *Appl. Phys. Lett.* **91** 082907

[6] Zhao X Y, Liu S J, Zhu J H, Dai N and Hu G J 2008 *Chin. Phys. Lett.* **57** 5968

[7] Zhu Z Y, Wang B, Wang H, Zheng Y and Li Q K 2007 *Chin. Phys.* **16** 1009

[8] Roytburd A L, Zhong S and Alpay S P 2005 *Appl. Phys. Lett.* **87** 092902

[9] Im J, Auciello O and Streiffer S K 2002 *Thin Solid Films* **413** 243

[10] Bao D H, Lee S K, Zhu X H, Alexe M and Hesse D 2005 *Appl. Phys. Lett.* **86** 082906

[11] Shimuta T, Nakagawara O, Makino T, Arai S, Tabata H and Kawai T 2002 *J. Appl. Phys.* **91** 2290

[12] Bao D H, Zhu X H, Alexe M and Hesse D 2005 *J. Appl. Phys.* **98** 014101

[13] Ohya Y, Ito T and Takahashi Y 1994 *Jpn. J. Appl. Phys.* Part 1 **33** 5272

[14] Tabata H, Tanaka H and Kawai T 1994 *Appl. Phys. Lett.* **65** 1970

[15] Wu J G, Zhu J L, Xiao D Q and Zhu J G 2007 *Appl. Phys. Lett.* **91** 212905

[16] Ranjith R, Nikhil R and Krupanidhi S B 2006 *Phys. Rev.* B **74** 184104

[17] Sim C H, Zhou Z H, Gao X S, Soon H P and Wang J 2008 *J. Appl. Phys.* **103** 034102

[18] Qu B D, Zhong W L and Prince R H 1997 *Phys. Rev.* B **55** 11218

[19] Shen J and Ma Y Q 2000 *Phys. Rev.* B **61** 14279

[20] Wu Y Z, Yu P L and Li Z Y 2002 *J. Appl. Phys.* **91** 1482

[21] Chew K H, Ong L H, Osman J and Tilley D R 2000 *Appl. Phys. Lett.* **77** 2755

[22] Ong L H, Osman J and Tilley D R 2002 *Phys. Rev.* B **65** 134108

[23] Yang B, Zhang D M, Zheng C D, Wang J and Yu J 2007 *J. Phys.* D: *Appl. Phys.* **40** 5696

[24] Essaoudi1 I, Ainane A, Saber M and de Miguel J J 2007 *Phys. Stat. Sol.* (B) **244** 3398

[25] Neaton J B and Rabe K M 2003 *Appl. Phys. Lett.* **82** 1586

[26] Lü T and Cao W 2002 *Phys. Rev.* B **66** 024102