Journal of Ceramic Processing Research. Vol. 11, No. 3, pp. 316~321 (2010)

J O U R N A L O F
Ceramic Processing Research

Low loss dielectric ceramics for microwave applications: a review

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Microwave dielectric ceramics have been used for a wide range of applications from wireless communication (including mobile communication, ultra high speed local area networks, intelligent transport system, satellite communication) to consumer electronic products. The need for portable, light weight and multifunctional electronic components has forced scientists to search for new advanced microwave materials. During the past 25 years, a large number of dielectric materials have been developed and the properties of existing materials have been improved. However, the data on these very useful materials are scattered. The main purpose of this review is to bring together the data of low loss microwave dielectric ceramics and classify them according to their applications. This should be of immense help to researchers and technologists all over the world.

Key words: Dielectric, Ceramics, Permittivity, Quality factor, Temperature coefficient of resonant frequency.

Introduction

The early microwave systems, consisted of bulk metallic cavities, were huge and could not be integrated with microwave integrated circuits (MICs). Microwave devices were traditionally machined from metal, and coaxial RF connections were provided with connectors generally leading to expensive, heavy and bulky packages [1, 2]. These systems cannot meet the market demand for portable and low cost modules. However, electronic circuits for telecommunications, entertainment electronics and the automobile industry have to handle a steadily increasing amount of functions occupying as tiny a space as possible. Dielectric ceramics have replaced bulky metallic cavities in most microwave applications for reasons of cost, dimension, mass, stability, efficiency, ruggedness and ease of use [3]. Also, the temperature coefficient of the resonant frequency can be engineered to a desired value to meet circuit designer's requirements.

Wireless communication has been a fast growing industry in recent years. Various applications include wireless FAX, cellular phones, global position satellite (GPS), military radar systems, intelligent transport system (ITS) and direct broadcast satellites. Dielectric ceramics are being used to make a variety of components such as resonators, filters and oscillators for these systems. Although a large numbers of dielectric materials have been developed, it has been difficult to have all the properties needed for practical applications at various operating frequencies in a single material at a reasonable cost. The advantages of these materials are that they are relatively cheap compared with some of the compounds currently used and in the future they can be improved even further by suitable additives and by optimizing the preparation conditions.

The main purpose of this paper is to gather together the research carried out, classify dielectric ceramics according to their application and discuss the performances of different low loss dielectric ceramic materials. Research work in this area is considerable and therefore it is difficult to present an exhaustive description of the subject in a single review. This review gives briefly the dielectric properties of some well known ceramics reported by various researchers.

Important characteristics of dielectric ceramics

The dielectric properties of a ceramic material determine its functionality. These properties include relative permittivity or dielectric constant (ε_r), quality factor Q which is the inverse of the dielectric loss ($\tan\delta$) and the temperature coefficient of the resonant frequency (τ_f).

Relative permittivity ε_r

The relative permittivity is an important parameter deciding the application of the ceramic. It should be high (20-100) for miniaturization of mobile equipment. The permittivity is related to the resonant frequency (f_0) of the dielectric resonator by the relation [3]: $f_0 \approx c/(\lambda_d \varepsilon_r^{1/2}) \approx c/(D\varepsilon_r^{1/2})$, where c is the speed of the light in a vacuum and λ_d is the wavelength of the standing wave along the diameter (D) of the resonator. Consequently, if the permittivity is increased, the size of the resonator may be decreased while still maintaining a specific resonant frequency, i.e. larger permittivities enable miniaturization.

Low relative permittivity materials in the range of 4-12 are used for millimetrewave communications and also as substrates for microwave integrated circuits. High speed signal propagation with minimum attenuation is an important aspect which is a direct function of the relative

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permittivity. In these applications, the relative permittivity (ε_r) governs the propagation delay t_d, which is given by the relation [4] : $t_d = (\sqrt{\varepsilon_r})/c$, where c is the speed of light in vacuum. Thus materials with low relative permittivity are required to increase the speed of the signal.

Quality factor

One of the important characteristics required for a dielectric material is a high quality factor Q (> 1,000 GHz) which is the inverse of the dielectric loss, tanδ. The quality factor is determined by the ratio of resonant frequency (f_0) to the bandwidth, Δf_0, measured at 3db below the maximum height at resonance, Fig. 1 [3]. This shows that Q is a measure of the selectivity of a resonator to a given frequency. Higher Q values reduce the risk of cross talk within a given frequency range. Q changes with change in frequency. The theoretical relationship between the two is such that $Q \times f_0$ should be constant and often $Q \times f_0$ are quoted when comparing materials [3].

Temperature coefficient of the resonant frequency

The variation of the dielectric properties of ceramics with temperature is very crucial for practical applications. The temperature coefficient of the resonant frequency (τ_f) is a measure of the drift in the resonant frequency with respect to temperature. It is evident that a material with a significantly large τ_f is not useful in a microwave circuit as it cannot maintain its resonant frequency with changes in the operating temperature [3]. The τ_f with a value of 10 ppm/K causes a 0.11% shift of the resonant frequency (5.7 MHz at 5.2 GHz) within the temperature range from –30 to +80 °C, a common temperature range of operation for mobile communication. Large τ_f values are undesirable as temperature compensation requires additional mechanical structures or electrical circuits [5]. The temperature coefficient of the resonant frequency τ_f of the resonator material should be close to zero for thermal stability of the device frequency. The τ_f is related to temperature coefficient of relative permittivity (τ_ε) and the coefficient of thermal expansion (α) by the relation [3] : $\tau_f = -(\tau_\varepsilon/2 - \alpha)$. It is also related to the temperature coefficient of capacitance (τ_c) by the relation [3] : $\tau_f = -(\tau_c - \alpha)/2$.

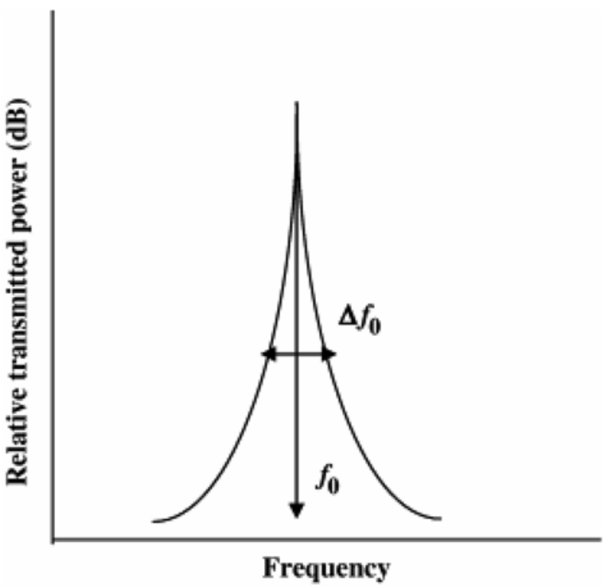

Fig. 1. Schematic showing a resonant peak and associated parameters.

Classification of dielectric ceramics

The low loss dielectric ceramics developed for various applications can be classified into three categories. The first category includes ceramics with low permittivity and ultra high Q used for millimetrewave and substrate applications. The second class with medium permittivity (25-50) and high Q are used for satellite communication and in cellular phone base station direction. The third category consists of high ε_r materials used in mobile phones where miniaturization of a device is very important. These categories of microwave dielectric materials are shown in Fig. 2, in which the quality factor Q.f is plotted as a function of the dielectric constant [6]. Curves in the figure shows an outline of the upper limit of Q.f obtained up to now for a given ε_r. The following sub-sections classify the important compositions researched and give the microwave properties reported.

Ceramics with low permittivity and ultra high Q

Wireless communications have been tremendously developed in the recent ubiquitous age. The utilizable frequency range has been extended to millimetrewaves because of a shortage of the conventional frequencies region. For ultra high frequencies of millimetrewaves and substrate applications, dielectrics with a ultra high quality factor Q and low dielectric constant are desired. Alumina, forsterite and willemite are some of the candidates for this category of dielectrics with ultra high Q and low ε_r.

Alumina

Alumina is a well-known ceramic packaging material. Powder purity is an important factor in the production of low-loss alumina [7-10]. In polycrystalline alumina, the presence of a very small amount of TiO_2 considerably improved the quality factor [7]. It was found [7] that

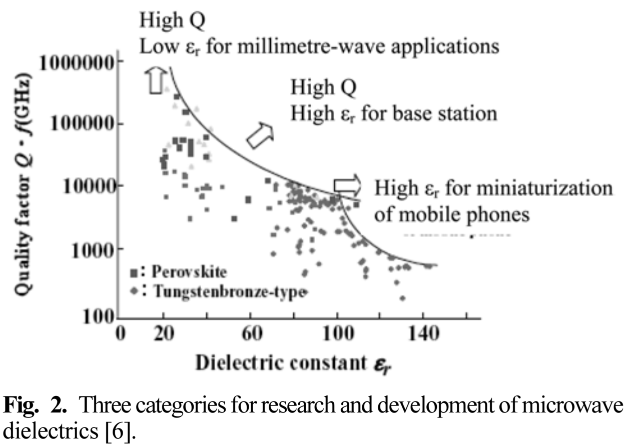

Fig. 2. Three categories for research and development of microwave dielectrics [6].

addition of 0.5 wt% TiO_2 lowers the sintering temperature to about 1500 °C with a considerable increase in the quality factor up to 50,300 at 9 GHz which is close to that of single-crystal sapphire. A Qf of 680,000 GHz with ε_r = 10.05 and τ_f = –60 ppm/°C was obtained in alumina ceramics sintered at 1550 to 1650 °C for 5 h [11].

Huang *et al*. [12, 13] found that the use of nano particle-sized starting material significantly improved the densification and microwave dielectric properties of alumina. The ε_r of 10, Q f value of 521,000 (at 14 GHz) and τ_f of –48.9 ppm/K were reported for α-Al_2O_3 ceramics without a sintering aid at 1550 °C for 4 h [12]. A sample containing 8 wt% of nano-TiO_2 sintered at 1350 °C for 4 hours had ε_r = 10.8 with Qf = 338,000 GHz and τ_f = 1.3 ppm/K [13].

Forsterite ceramics

Ohsato and coworkers [14-16] reported forsterite (Mg_2SiO_4) as a high Q material for millimetre wave communication as well as a substrate for the MICs. Tsunooka *et al*. [15] reported that high-Q plain forsterite ceramics with Q.f = 240,000 GHz were developed by the usual solid sintering process using highly purified MgO and SiO_2 as raw materials. The composition prepared with an addition of 1 wt.% of TiO_2 exhibited a high Q.f value = 230,000 GHz with ε_r = 7.0 and τ_f = –65 ppm/K [15]. Latter on the Q.f of forsterite (Mg_2SiO_4) has been reported as 270,000 GHz with ε_f = 6.8, τ_f = –67 ppm/K by Ohsato *et al*. [16].

Willemite ceramics

Willemite (Zn_2SiO_4), another low-loss silicate useful as a substrate and in millimetre wave communication, has been successfully prepared by a solid state reaction in the temperature range from 1280 °C to 1340 °C [17]. The zine-silicate has an ultra-high Qf of 219,000 GHz and low ε_r = 6.6 and τ_f = –61 ppm/K. Guo *et al*. [17] tailored the high negative τ_f of willemite by the addition of TiO_2. The willemite–rutile mixture ceramics have excellent dielectric properties. It was found that an addition of 11 wt% TiO_2 sintered at 1250 °C resulted in a temperature-stable ceramic with ε_r = 9.3, Qf = 113,000 GHz and τ_f = 1 ppm/K [17]. Zou et al. reported that it was difficult to acquire dense ceramics at 1380 °C without sintering aids in the ZnO-SiO_2 system. The samples of ZnO-0.6SiO_2 with Li_2CO_3 and Bi_2O_3 additions sintered at 910 °C for 2 h showed excellent properties of ε_r = 6.65, Q.f = 33,000 GHz (at 11 GHz) and τ_f = –70 ppm/K. [18].

Ceramics with medium permittivity and high Q

Recently, as the number of base stations for telecommunications is increasing rapidly, the resonator is expected to reduce the size for installation and maintenance. So, new materials with medium-to-high permittivity are expected for miniaturization of resonators.

TiO_2 based systems

The $A_nLa_4Ti_{3+n}O_{12+3n}$ (A = Ba, Sr, Ca) [19-20] homologous compounds are excellent candidates for dielectrics of base stations with ε_r = 44.4, Q.f = 410,008 GHz, τ_f = –26 ppm/K for Ba ; ε_r = 43.7, Q.f = 46,220 GHz, τ_f = –8.4 ppm/K for Sr and ε_r = 41.1, Q.f = 50,246 GHz, τ_f = –25.5 ppm/K for the Ca analogue.

A few more candidate materials such as BaO- TiO_2-ZnO : ε_r = 36, Q.f = 42,000 GHz [21] and $ZnNb_2O_8$-TiO_2 : ε_r = 37, Q.f = 29,000 GHz have also been reported [22].

Zinc niobates

MNb_2O_6 (M = Ca, Co, Mn, Ni or Zn) ceramics are known [23] as useful microwave dielectric materials. $ZnNb_2O_6$ sintered at 1150 °C for 2 h has a Qf of 83,700 GHz and ε_r of 25.

(Mg,Ca)TiO_3

(Mg,Ca)TiO_3 is a very useful dielectric material for high frequency antenna applications. When sintered at ~1350 °C, ε_r is ~20, Qf is 86,000 GHz and τ_f is -3 ppm/K [24]. Its decomposition does not adversely affect the dielectric properties since $MgTi_2O_5$ has ε_r = 17.4 and Qf = 47,000 GHz and Mg_2TiO_4 has ε_r = 14.4 and Qf = 55,000 GHz.

ZnO-TiO_2 system

The ZnO-TiO_2 system contains $ZnTiO_3$ (hexagonal), Zn_2TiO_4 (cubic) and $Zn_2Ti_3O_8$ (cubic) [25]. The preparation of $ZnTiO_3$ from a mixture of ZnO and TiO_2 is difficult because the compound decomposes into Zn_2TiO_4 and rutile at ~945 °C [26]. Haga *et al*. [27] in 1992 reported for the first time the microwave dielectric properties of ZnO-TiO_2 ceramics. Later in 1998 Golovochanski *et al*. [28] reported that $ZnTiO_3$ can be sintered at the relatively low temperature of ~1100 °C with Qf = 30,000 GHz and ε_r = 19.

(Zr,Sn)TiO_4 having excellent high frequency properties (ε_r = 40, Qf = 53,000 GHz and τ_f = 50 ppm/K) has been used for microwave applications.

Tellurium based systems

Most tellurium based oxide materials can be synthesized and sintered at temperatures below 900 °C. Udovic *et al*. [29] reported that TeO_2 has a poor sinterability and the ceramic sintered at 640 °C for 15 h has 20% porosity with ε_r = 19.3, Q.f = 30,000 GHz and τ_f = –119 ppm/K. Many authors [29-30] have reported the synthesis of $TiTe_3O_8$ with a cubic unit cell from oxides at 700 °C. Kwon *et al*. [31] reported that it is difficult to prepare it as a dense ceramic. Udovic et al. [29] prepared single phase dense $TiTe_3O_8$ by muffling in TeO_2 powder and the samples showed ε_r of 50 and Qf of 30,600 GHz, but the τ_f was +133 ppm/K.

Bi_2O_3-Nb/Ta based compounds

Mixed dielectric structures combine the attributes of high and low relative permittivity materials. Low ε_r substrates are useful for impedance matching transmission lines and for minimizing cross-talk. The incorporation of high ε_r bismuth pyrochlore capacitors in low ε_r substrates was found [32] to decrease the band pass filter dimensions with an improvement in the overall filter characteristics. Kagata *et al*. [33] also investigated the microwave dielectric properties of bismuth-based compounds. They reported that $BiNbO_4$ ceramics is difficult to sinter without additives. An addition of small amounts of CuO or V_2O_5, CuV_2O_6, B_2O_3 to $BiAO_4$ (A = Nb/Ta) resulted in dense ceramics with ε_r in the range 40-45 and Qf up to 30,000 GHz and low τ_f when sintered at a temperature of 950 °C [34-39].

Ceramics with high permittivity

This sub-section will discuss the systems based on well known dielectric ceramics having high ε_r and high Qf for applications in mobile phone handsets.

TiO_2 systems

TiO_2 is widely researched as a basic ceramic for high permittivity ceramics. Several approaches including monosized [40] or nanosized [41] TiO_2 have been attempted to sinter TiO_2 ceramics at temperatures lower than 1000 °C. Kim *et al*. reported that the addition of CuO to anatase significantly lowered the sintering temperature. The final composition was a mixture of CuO and rutile [42] and with 2 wt-% addition of CuO sintered at 900 °C for 2 h, the ε_r, Qf and τ_f of 98, 14,000 GHz and 374 ppm/K were achieved.

Detvos *et al*. [43] studied the permittivity-frequency response of compressed TiO_2 being calcined under different conditions in the frequency range 20 Hz-1 MHz. The rutile microcrystal structure almost attains a relaxation-free permittivity response, with low loss characteristics in the frequency range examined. A calcination temperature of 1180 °C provides ceramics with a high packing micro-crystal density, having stable $\varepsilon_r = 12.3$ and $\tan\delta = 2.3 \times 10^{-3}$ (at 1 MHz).

BaO-TiO_2 system

The BaO-TiO_2 system is also widely used in microwave applications. The typical phases $BaTi_4O_9$ and $Ba_2Ti_9O_{20}$ are commonly sintered at about 1250 and 1300 °C, and ε_r and Qf are close to 36 and 50,000 GHz respectively. Additionally, the τ_f value depends on the formation of secondary phases, but can be very close to 0 ppm/K [44]. BaO-TiO_2 with 0.1 wt-%WO_3 (N-35) was found to show excellent microwave dielectric properties with ε_r = 35, Qf = 52,000 GHz and τ_f close to 0 ppm/K [45]. The sintered N-35 consists of $BaTi_4O_9$, $Ba_2Ti_9O_{20}$ and $BaWO_4$ phases. However, its sintering temperature is relatively high (1360 °C).

Wu *et al*. [46] prepared the BaO-TiO_2 system ceramics by a conventional mixed oxide route and reported the dielectric properties at 1 GHz as $\varepsilon_r = 37$, Q = 12,500 and $\tau_f = -29$ ppm/K. ZnO and Nb_2O_5 were added as sintering agents to lower the sintering temperature to 1260 °C. Weng *et al*. [47] successfully synthesized single phase $BaTi_4O_9$ powders and ceramics at a low processing temperature (1250 °C) by a polymeric precursor route. The dielectric properties of $BaTi_4O_9$ ceramics were dielectric constant = 35.6; a high Q.f value of 42,600 and the temperature coefficient of resonant frequency of 12 ppm/K.

BaO-R_2O_3-TiO_2 Tungsten bronze type system

The BaO-R_2O_3-TiO_2 (R = rare earth, Sm, Nd, Gd, Pr, La) in 1 : 1 : 4 or 1 : 1 : 5 compositions are excellent dielectric materials having high ε_r and high Qf especially suitable for dielectric resonators in mobile phone hand sets [6].

The tungsten bronze-type like $Ba_{6-3x}R_{8+2x}Ti_{18}O_{54}$ (R = rare earth) solid solutions sintered at ~1350 °C are well known microwave compositions having moderately high relative permittivity (70-100), high Qf (> 2,000 GHz) and low τ_f [47-52]. Similar results for Sm and Nd systems have been reported by Negas *et al*. [53]. The characteristic phenomenon is that Qf values varied non linearly as a function of composition, although ε_r and τ_f vary proportionally to the composition.

The $Ba_{6-3x}R_{8+2x}Ti_{18}O_{54}$ ceramics with x = 2/3 shows the highest Qf values: 10,549 GHz in Sm analogue, 10,010 GHz in the Nd analogue and 2,024 GHz in the La-analogue.

Bi_2O_3 based compounds

Among the bismuth-based ceramics, Bi_2O_3-ZnO-Nb_2O_5 (BZN) ternary oxides have received considerable attention. Several research groups [54-57] studied the structure and properties of BiO-ZnO-Nb_2O_5 ceramics. There are two main phases in BZN, a cubic pyrochlore phase $Bi_{1.5}ZnNb_{1.5}O_7$ (α-phase) with ε_r ~150 and τ_f about −400 ppm/K, and a monoclinic zirconolite like phase $Bi_2Zn_{2/3}Nb_{4/3}O_7$ (β-phase) with ε_r ~ 80 and τ_f about +150 ppm/K. Several authors [58-61] reported that BZN are temperature-stable dielectrics suitable for the capacitor industry with a sintering temperature of ~1000 °C. Yan *et al*. [59] proposed that the sintering temperature can be further lowered below 950 °C by incorporating Bi_2O_3-NiO-Nb_2O_5 into BZN ceramics. Several authors investigated the microwave dielectric properties of Bi_2O_3-ZnO-Nb_2O_5/Ta_2O_5 ceramics [62-65].

Finally, Bi can be partially substituted by La, Nd, Sm, Ce and Nb/Ta by Mo, Sb, etc. [66-69].

Li based systems

Borisevich and Davies reported [70-71] that $Li_{1+x-y}M_{1-x-3y}Ti_{x+4y}O_3$ (M = Nb/Ta; x = 0.1; y = 0.05–0.175) solid solutions are potential candidate materials for microwave applications with a quality factor up to 10,500 GHz when sintered at 1100 °C. However, volatile Li has a deleterious effect on dielectric properties in Li-based ceramics and the deficiency of Li lead to a decrease in density and lattice defects.

Ag based systems

The $AgNbO_3$ and $AgTaO_3$ compounds represent a class of materials with high relative permittivity greater than 400 with Qf in the range 600-900 GHz [72-74]. In general, these compounds undergo a series of structural phase transitions as they cool from the prototypic cubic perovskite phase and $AgNbO_3$ exhibits a weak ferroelectric behavior at room temperature.

Conclusions

Microwave dielectric ceramics are being developed for a variety of applications such as miniaturization for mobile phones, a transmitter and receiver with high performance for base station, and millimetrewave applications for ultra speed wireless LAN and ITS. They have been characterized according to these major applications. Microwave dielectric properties reported by various researchers have been summarized for important ceramic systems. This review will provide a vital guideline for further development.

References

1. H. Liang, H.L. Barnes, J. Laskar and D. Estrich, IEEE Trans. Microwave Theory Tech. 48 (2000) 2644–2651.
2. T.A. Midford, J.J. Wooldridge and R.L. Sturdivant, IEEE Trans. Antenna and Propagation 43 (1995) 983-991.
3. A.J. Moulson and J.M. Herbert, “Electroceramics” (Champman and Hall, London, 1990).
4. R.C. Buchanan, “Ceramic Materials for Electronics” (Marcel Dekker, New York, 1986).
5. H. Jantunen and A. Turunen, US Patent 5302924, 1994, USA.
6. H. Ohsato, J. Ceram Soc. Jpn. 113[11] (2005) 703-711.
7. N.M. Alford and S.J. Penn, J. Appl. Phys. 80 (1996) 5895-5898.
8. J. Molla, R. Heidinger and A. Ibarra, J. Nucl. Mater. 212-215 (1994) 1029-1034.
9. J. Molla, M. Gonzalez, R. Vila and A. Ibarra, J. Appl. Phys. 85 (1999) 1727-1730.
10. A. Ibarro, R. Heidinger and J. Molla, J. Nucl. Mater, 191-194 (1992) 530-534.
11. H. Ohsato, T. Tsunooka, M. Ando, Y. Ohishi, Y. Miyauchi and K. Kakimoto, J. Korean Ceram. Soc. 40 (2003) 350-353.
12. C.-L. Huang, J.-J. Wang and C.-Y. Huang, Mater. Lett. 59 (2005) 3746-3749.
13. C.-L. Huang, J.-J.Wang and C.-Y. Huang, J. Am. Ceram. Soc. 90 (2007) 1487-1493.
14. H. Ohsato, T. Tsunooka, A. Kan, Y. Ohishi, Y. Miyauchi, T. Tohda, T. Okawa, K. Kakimoto and H. Ogawa. Key Eng. Mater. 269 (2004) 195-198.
15. T. Tsunooka, M. Androu, Y. Higashida, H. Sugiura and H. Ohsato, J. of Eur. Ceram. Soc. 23 (2003) 2573-2578.
16. H. Ohsato, T. Tsunooka, T. Sugiyama, K.-I. Kakimoto and H. Ogawa, J. Electroceram. 17 (2006) 445-450.
17. Y. Guo, H. Ohsato and K.-I. Kakimoto, J. Eur. Ceram. Soc. 26 (2006) 1827-1830
18. J.-L. Zou, Q.-L. Zhang, H. Yang and H.-P. Sun, Jpn. J. Appl. Phys. 45 (2006) 4143-4145.
19. T. Okawa, K. Kiuchi, H. Okabe and H. Ohsato, Jpn. J. Appl. Phys. 40 (2001) 5779-5782.
20. Y. Tohdo, K. Kakimoto, H. Ohsato, H. Yamada and T. Okawa, J. of Eur. Ceram. Soc. 26 (2006) 2039-2043.
21. S. Wu, G. Wang, Y. Zhao and H. Su, J. Eur. Ceram. Soc. 23 (2003) 2565-2568.
22. D.-W. Kim, K.H. Ko, D.-K. Kwon and K. S. Hong, J. Am. Ceram. Soc. 85 (2002) 1169-1172.
23. H.-J. Lee, K.-S. Hong, S.-J. Kim and I.-T. Kim, Mater. Res. Bull. 32 (1997) 847-855.
24. I.-S. Kim, W.-H. Jung, Y. Inaguma, T. Nakamura and M. Itoh, Mater. Res. Bull. 30 (1995) 307-316.
25. O. Yamaguchi, M. Morimi, H. Kawabata and K. Shimizu, J. Am. Ceram. Soc. 70 (1987) C-97-C-98.
26. Y.-S. Chang, Y.-H .Chang, I.-G. Chen, G.-J. Chen, Y.-L. Chai, S. Wu and T.-H. Fang, J. Alloys Compd 354 (2003) 303-309.
27. K. Haga, T. Ishiji, J. Mashiyama and T. Ikeda, Jpn J. Appl. Phys. 31 (1992) 3156-3159.
28. A. Golovochanski, H. T. Kim and Y. H. Kim, J. Korean Phys. Soc., 1998, 32, S1167-S1169.
29. M. Udovic, M. Valant and D. Suvorov, J. Eur. Ceram. Soc. 21 (2001) 1735-1738.
30. S. Yamanaka and M. Miyake, J. Less-Common Met. 159 (1990) 179-189.
31. D.-K. Kwon, M.T. Lanagan and T.R. Shrout, J. Ceram. Soc. Jpn. 113 (2005) 216-219.
32. A. Baker, M. Lanagan, C. Randall, E. Semouchkina, G. Semouchkin, K.Z. Rajab, R. Eitel, R. Mitra, S. Rhee, P. Geggier, C. Duschl and G. Fuhr, Int. J. Appl. Ceram. Technol. 2 (2005) 514-520.
33. H. Kagata, T. Inoue, J. Kato and I. Kameyama, Jpn J. Appl. Phys. 31 (1992) 3152-3155.
34. H.R. Lee, K.H. Yoon and E.S. Kim, Jpn J. Appl. Phys. 42 (2003) 6168-6171.
35. E.S. Kim and W. Choi, J. Eur. Ceram. Soc. 26 (2006) 1761-1766.
36. C.-L. Huang, M.-H. Weng and C.-C. Yu, Ceram. Int. 27 (2001) 343-350.
37. C.-L. Huang and M.-H. Weng, Mater. Lett. 43 (2000) 32-35.
38. C.-L. Huang, M.-H. Weng and G.-M. Shan, J. Mater. Sci., 35 (2000) 5443-5447.
39. D. Shihua, Y. Xi and Y. Yong, Ceram. Int. 30 (2004) 1195-1198.
40. E.A. Barringer and H. K. Bowen, J. Am. Ceram. Soc. 65 (1982) C199-C201.
41. H. Hahn, J. Logas and R. S. Averback, J. Mater. Res. 5 (1990) 609-614.
42. D.-W. Kim, B. Park, J.-H. Chung and K. S Hong, Jpn J. Appl. Phys. 39 (2000) 2696-2700.
43. C.T. Dervos, Ef. Thirios, J. Novacovich, P. Vassiliou, P. Skafidas, Materials Letters 58 (2004) 1502-1507.
44. J.-H. Choy, Y.-S. Han, J.-H. Sohn and M. Itoh, J. Am. Ceram. Soc. 78(1995) 1169-1172.
45. S. Nishigaki, S. Yano, H. Kato, T. Hirai and T. Nonomura, J. Am. Ceram. Soc. 71 (1988) C-11-C-17.
46. S. Wu, G. Wang, Y. Zhao and H. Su, J. Eur. Ceram. Soc. 23 (2003) 2565-2568.
47. M.H. Weng, T.J. Liang and C.L. Huang, J. Eur. Ceram. Soc. 22 (2002) 1693-1698.
48. H. Ohsato, T. Ohhashi, S. Nishigaki, T. Okuda, K. Sumiya and S. Suzuki, Jpn. J. Appl., Phys. 32 (1993) 4323-4326.
49. H. Ohsato, T. Ohhashi, H. Kato, S. Nishigaki and T. Okuda, Jpn. J. of Appl. Phys. 34 (1995) 187-191.
50. H. Ohsato, M. Mizuta, T. Ikoma, Y. Onogi, S. Nishigaki and T. Okuda, J. Ceram. Soc. of Japan 106 (1998) 178-182.
51. H. Ohsato, J. Eur. Ceram. Soc. 21 (2001) 2703-2711.
52. H. Ohsato, M. Suzuki and K. Kakimoto, Ceram. Eng. and Sci. Proceedings 26 (2005) 135-145.
53. Negas, T., Davies, P.K. (1995) Material and Processes for Wireless Communications Ceramic Transactions, 53, pp. 179-196.
54. I. Levin, T.G. Amos, J.C. Nino, T.A Vanderah, I.M. Reaney,

C.A. Randall and M.T. Lanagan, J. Mater. Res. 17 (2002) 1406-1411.
55. M. Valant and P. K. Davies, J. Am. Ceram. Soc. 83 (2000) 147-153.
56. H.-J. Youn T. Sogabe, C.A. Randall, T.R. Shrout and M.T. Lanagan, J. Am. Ceram. Soc., 2001, 84, 2557-2562.
57. H. Du, X. Yao and L. Zhang, Ceram. Int. 28 (2002) 231-234.
58. H.C. Ling, M.F. Yan and W.W. Rhodes, J. Mater. Res. 5 (1990) 1752-1762.
59. M.F. Yan, H.C. Ling and W.W. Rhodes, J. Am. Ceram. Soc. 73 (1990) 1106-1107.
60. X. Wang, H. Wang and X. Yao, Structures, J. Am. Ceram. Soc. 80 (1997) 2745-2748.
61. D. Liu, Y. Liu, S.-Q. Huang and X. Yao, J. Am. Ceram. Soc. 76 (1993) 2129-2132.
62. S.L. Swartz and T.R. Shrout, US Patent 5449652 (1995) USA.
63. D.P. Cann, C.A. Randall and T.R. Shrout, Solid State Commun. 100 (1996) 529-534.
64. H.-J. Youn, C. Randall, A. Chen, T. Shrout and M.T. Lanagan, J. Mater. Res. 17 (2002) 1502-1506.
65. H.B. Hong, D.-W. Kim and K.S. Hong, Jpn J. Appl. Phys. 42 (2003) 5172-5175.
66. N. Wang, M.-Y. Zhao, W. Li and Z.-W. Yin, Ceram. Int. 30 (2004) 1017-1022.
67. Y.-C. Chen, W.-C. Tzou, C.-F. Yang and P.-S. Cheng, Jpn J. Appl. Phys. 40 (2001) 3252-3155.
68. C.-L. Huang, M.-H. Weng and C.-C. Wu, Jpn J. Appl. Phys. 39 (2000) 3506-3510.
69. N. Wang, M.-Y. Zhao, Z.-W. Yin and W. Li, Mater. Res. Bull 39 (2004) 439-448.
70. A. Borisevich and P.K. Davies, J. Eur. Ceram. Soc. 21 (2001) 1719-1722.
71. A.Y. Borisevich and P.K. Davies, J. Am. Ceram. Soc. 85 (2002) 573-578.
72. M. Valant, D. Suvorov and A. Meden, J. Am. Ceram. Soc. 82 (1999) 81-87.
73. M. Valant, D. Suvorov and A. Meden, J. Am. Ceram. Soc. 82 (1999) 88-93.
74. M. Valant, D. Suvorov, C. Hoffmann and H. Sommariva, J. Eur. Ceram. Soc. 21 (2001) 2647-2651.