Comparison of Paraelectric and Ferroelectric Materials for Applications as Dielectrics in Thin Film Integrated Capacitors

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Abstract

Ferroelectrics such as BaTiO$_3$, PbZr$_{1-x}$TiO$_3$, and Ba$_x$Sr$_{1-x}$TiO$_3$ can exhibit dielectric constants up to three orders of magnitude higher than those of paraelectric materials such as SiO$_2$, Al$_2$O$_3$, Ta$_2$O$_5$, and BCB. However, the dielectric properties of ferroelectrics are typically a stronger function of temperature, frequency, film thickness, and bias resulting in significant nonlinearities in their performance. Also, the dielectric constant of some ferroelectrics degrades with time. As a result, paraelectrics are more suitable for high-tolerance applications such as filtering, timing, RF/wireless, and A/D where constant, predictable capacitance is required. Ferroelectrics would be preferred for decoupling due to their higher dielectric constants and due to the fact that less tolerance is necessary; the capacitor only needs to meet a certain minimum value. Either might be used for termination as long as footprint requirements can be met. Annealing temperatures for high-k ferroelectrics are currently excessive for applications on organic boards which complicate their integration into these substrates. Since capacitor values on a single board might span up to six orders of magnitude, it may be necessary to use more than one dielectric material to restrict the capacitor footprints to an acceptably smaller range. BCB and SiO$_2$ may be more useful for these low values and may be already present on the substrate as an interlayer dielectric.

Key words:
Integrated Capacitors, Integrated Passives, Dielectric Materials, and Dielectric Constant.

1. Introduction

In the coming years, capacitors will be increasingly fabricated into microelectronic substrates in some manner since there are clear benefits in functional density, performance, and reliability relative to surface mount discretes. The main questions to be resolved involve the choice of materials, configurations, and fabrication processes to implement integrated capacitors in a cost-

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bias, impurity concentration, and crystal structure. The three mechanisms of charge storage are briefly reviewed for the two classes in order to elucidate the differences in fabrication options, electrical performance, and the effects of operational conditions such as temperature, bias, frequency, and film thickness. Then, the two types of dielectrics are compared, based on these physical and electrical properties, for use in the integrated capacitor applications of decoupling, analog functions, and termination. It will be shown that the fundamental difference in the way the two materials store charge is very important to their respective suitability for these applications. It will also be shown that selecting the dielectric with the largest k is not always the optimal choice. Broad criteria for the selection of materials for integrated dielectrics will be given as a function of application, footprint requirements, and substrate material.

2. Mechanisms of Dielectric Charge Storage

The ability of a dielectric material to store energy under the influence of an electric field results from the separation and alignment of electric charges brought about by that field. The larger the dipole moment arm, the separation of charges in the direction of the field, and the larger the number of these dipoles, the higher the material’s dielectric constant. There are several possible contributions to this polarizability which, depending on the mechanisms operative in a given dielectric, determine not only the value of k, but also how it varies with frequency, temperature, bias, impurity concentration, and crystal structure. The three general mechanisms important to candidate materials for integrated capacitors are electronic, atomic, and ionic polarization.

Electronic polarization involves charge symmetry distortion of an atom. Under the influence of an applied field the nucleus and the negative charge center of the electrons shift in opposite directions creating a small dipole. This induced dipole effect occurs in all materials, including air, but is usually very small compared to other polarization mechanisms since the moment arms of these dipoles are very short, usually a fraction of the size of an atom. Atomic polarization occurs in substances made up of more than one type of nonionic atom due to the different elements will not normally share the electron cloud equally; it will be shifted towards the more electronegative atoms resulting in a permanent dipole. The electric field will then produce opposite forces on various parts of the molecules causing the atoms to move to create the alignment of charges and field. It is the movement of charges aligning with the field which creates capacitance, not the presence of permanent dipoles. If these randomly-oriented permanent dipoles were somehow not capable of movement and alignment, there would be no dielectric constant for that material above that of a vacuum. Therefore, k is a function of the material’s structure and lattice flexibility as well as its composition. Ionic polarization is similar to atomic polarization but involves the shifting of ionic species under the influence of the field which can lead to very high dielectric constants, up to several thousand.

Both paraelectric and ferroelectric materials exhibit electronic, atomic, and ionic polarization; the two classes of materials are not distinguished from one another in that regard. The distinguishing feature is that ferroelectric materials do not lose their ionic polarization when the field is removed and paraelectrics do. Due to the lattice hindrances in ferroelectrics, the electric field can pull the ions into configurations that do not relax back to the previous state once the field is removed. As a result, ferroelectrics, analogous to ferromagnetic, materials, can possess a residual polarization after the field is removed. Furthermore, this residual polarization can be oriented in one direction or the other depending on the direction of the last field. It is this trait that gives them utility in non-volatile memories. Paraelectric materials are those which cannot be left with a residual polarization once the field is removed since they do not have a mobile charged atom with more than one stable lattice position.

This residual polarizability defines ferroelectric and paraelectric materials but this feature is irrelevant to any projected substrate-level integrated capacitor application. The important difference from the point of view of integrated passives is that ferroelectrics generally have much greater dielectric constants than do paraelectrics, sometimes by as much as three orders of magnitude, due to the mobile ionic charge. For example, the common ferroelectric barium titanate is a perovskite crystal with a Ti cation at the center which can shift back and forth within the confines of this crystal a distance larger than the ions can move in a typical paraelectric such as tantalum oxide. This motion creates a considerably larger dipole arm than is possible in TaO5 resulting in a much larger dielectric constant for BaTiO3. Incidentally, it is the fact that this Ti ion can remain shifted to one side or the other after the field is removed that gives BaTiO3 its ferroelectric residual polarization behavior.

Table 1 shows the dielectric constants for ten paraelectrics and four ferroelectrics clearly showing the wide difference between them. The k’s given for the ferroelectrics are maximum amounts since their specific values depend on grain size, crystal orientation, electrical bias, frequency of measurement, and film thickness. Ferroelectrics must possess a crystal structure in order to exhibit these high dielectric constants otherwise their k’s are no higher than typical paraelectrics. The dielectric constant of amorphous barium titanate is comparable with paraelectrics at a value of about 17 since the polarization contribution of the Ti moving in the crystal cage is lost when there is no crystal structure to support it. The values for ferroelectrics in Table 1 are for completely oriented bulk material single crystals at low frequency and no bias. Therefore, they represent maximum ranges of values for these materials. The dielectric constant for ferroelectrics is so highly dependent on processing and measurement conditions that it is not possible to be more specific but the values given for paraelectrics are only weakly dependent on how they are fabricated or how the k’s are measured and represent typi-
Method is not suitable for paraelectrics since the mixture of these can be achieved in advance of application to the substrate. This temperature steps necessary to obtain high k from ferroelectrics, this method is that much of the processing, and all of the high processing conditions. Some of the fabrication methods germane to integrated capacitors are outlined next.

In general, ferroelectric materials must achieve a crystalline or polycrystalline state in order to exhibit higher dielectric constants than paraelectrics. This may require anneal temperatures of 500 - 700°C in oxygen which precludes the use of this technology on some common substrates. Most paraelectric materials are amorphous and their dielectric constants are relatively insensitive to crystalline phases. This restricts the choice for the bottom electrode. Thickness control is achieved through the final voltage of the anodization cell. For Ta, the thickness of the resulting dielectric oxide is 16 Å per anodizing volt and it is only a weak function of the processing time or current density. The resulting Ta2O5 films have a k of about 24, two orders of magnitude below deposited and annealed ferroelectrics. BaTiO3 has been made by anodization without a high-temperature anneal but, to date, with poorer dielectric properties than sol-gel films which were subsequently thermally cured.

Anodization avoids this roughness problem since a thick layer of anodizable metal can be deposited, either Al or Ta, and the anodization procedure can be controlled to convert only enough metal into dielectric as is necessary to achieve the desired specific capacitance. Therefore, the composition or roughness of the metal underlying the Al or Ta is not an issue, and this approach avoids having to planarize and monitor the state of the bottom electrode. Thickness control is achieved through the final voltage of the anodization cell. For Ta, the thickness of the resulting dielectric oxide is 16 Å per anodizing volt and it is only a weak function of the processing time or current density.

The electrical properties of any dielectric are a function of its chemical composition and crystal morphology which, in turn, are influenced by the technique used to form the material. There are many ways to create dielectric films including spin-coating, sputtering, CVD, MOCVD, sol-gel, pulse-laser deposition, anodization, dry calcination, hydrothermal, among many techniques. In general, ferroelectric materials must achieve a crystalline or polycrystalline state in order to exhibit higher dielectric constants than paraelectrics. This may require anneal temperatures of 500 - 700°C in oxygen which precludes the use of this technology on some common substrates. Most paraelectric materials are amorphous and their dielectric constants are relatively insensitive to processing conditions. Some of the fabrication methods germane to integrated capacitors are outlined next.

BaTiO3 powder can be made by dry calcination of BaCO3 and TiO2 at temperature >1200°C resulting in particles 1000 - 2000 Å in diameter with dielectric constants in the low thousands. These or other types of ferroelectric high k particles can be mixed with epoxy up to 70% loading by volume, cast in thin film form, and the epoxy cured at under 200°C. The mixing rules for two materials of different dielectric constants are such that the dielectric constant of the final composite will be much closer to that of the low k material which is generally an epoxy with a k of about 3 to 5. The overall dielectric constant will end up being around 30 - 100. The result is films as thin as 1 micron which can be made pinhole-free with some tens of nF/cm2. The advantage of this method is that much of the processing, and all of the high temperature steps necessary to obtain high k from ferroelectrics, can be achieved in advance of application to the substrate. This method is not suitable for paraelectrics since the mixture of these much lower-k powders with epoxy would have about the same dielectric constant of the epoxy alone.

A number of sol-gel methods have been developed for ferroelectrics which result in films of under 1 μm and dielectric constants in the low thousands. These techniques can give specific capacitances of thousands of nF/cm2 but require a high temperature cure to achieve the necessary crystal structure. Currently, there are some aqueous routes at temperatures as low as 100°C to make high-k BaTiO3 but the solution must be very alkaline, as high as pH 14.

CVD, laser-ablation, MOCVD, and sputtering of ferroelectrics and paraelectrics have been practiced for decades. Again, the ferroelectrics will usually require a high temperature cure to achieve the very high-k values which result from the crystal structure. For sputtered dielectrics of any sort, the roughness of the bottom electrode is critically important since steep slopes might not be sufficiently covered resulting in unacceptable leakage or even shorts. Most investigations of implementing a sputtering procedure for integrated capacitors end up being fixated on this issue in order to bring the yield up to acceptable levels. As a result, obtaining acceptable yields for sputtered integrated capacitors with either dielectric type on Kapton and alumina substrates is more difficult than it is on Si due to the inherently higher roughness of these materials.

Anodization avoids this roughness problem since a thick layer of anodizable metal can be deposited, either Al or Ta, and the anodization procedure can be controlled to convert only enough metal into dielectric as is necessary to achieve the desired specific capacitance. Therefore, the composition or roughness of the metal underlying the Al or Ta is not an issue, and this approach avoids having to planarize and monitor the state of the bottom electrode. Thickness control is achieved through the final voltage of the anodization cell. For Ta, the thickness of the resulting dielectric oxide is 16 Å per anodizing volt and it is only a weak function of the processing time or current density.

The resulting Ta2O5 films have a k of about 24, two orders of magnitude below deposited and annealed ferroelectrics. BaTiO3 has been made by anodization without a high-temperature anneal but, to date, with poorer dielectric properties than sol-gel films which were subsequently thermally cured.

Most ferroelectric deposition methods (CVD, MOCVD, sputtering) require an oxidizing atmosphere of 500 - 700°C to form crystalline phases. This restricts the choice for the bottom electrode to nonoxidizable materials such as Pt or Au. Other metals, such as Al or Cu, react to form their own oxides which, for thin dielectrics, will dominate the overall dielectric constant of the two layers through the mixing rule mentioned earlier for powders in epoxy. Pt is popular as the base electrode since, in addition to thermodynamic stability, it has a high Schottky barrier and, therefore, a lower leakage for thin films. Figure 1 shows the measured dielectric constant of sputtered ferroelectric PZT and BST films deposited on Pt as a function of film thickness along with paraelectric Ta2O5. Substrate effects such as stress, defects, grain size, and interdiffusion restrict the ferroelectric’s dielectric constant to values below those of the bulk material until...
the film is at least a few thousand angstroms thick. These same films show a higher $k$ on Pt than on stainless steel due to better lattice match. There is no film thickness or substrate composition dependencies for paraelectrics in general.

Regardless of the deposition method, the dielectric constant of most ferroelectric materials is a function of the film stoichiometry, crystal structure, substrate characteristics, interfacial reactions, microstructural heterogeneities, lattice defects, mechanical stresses, film thickness, and electrode material. Amorphous paraelectrics are largely immune to all of these effects but at the cost of a much lower $k$.

4. Operational Effects on Dielectric Constants

Temperature, frequency, and bias can affect the dielectric constant of both paraelectric and ferroelectric dielectrics by acting through the relevant polarization mechanisms. For instance, when a high frequency field is applied, the dipole must reverse direction at the same rate for the polarization to remain in synchronization with the field. As the frequency increases, it may outrun the ability of the particular dipole to keep up with the reversals resulting in the dipole arm being effectively shortened, resulting in a decrease in dielectric constant. Of the charge storage mechanisms described above, only the Ti motion in ferroelectrics is affected at frequencies below the infrared range. Figure 2 shows the ratio of the dielectric constant measured at various frequencies to the value at 100 Hz. The peaks in the BaTiO$_3$ data are due to crystal transitions, such as the tetragonal to cubic conversion at 120°C. Some ferroelectrics can be modified with additives to reduce temperature dependencies.

Most paraelectrics exhibit moderate positive temperature coefficients of capacitance, generally from +100 to +400, near room temperature and similar to PZT. The common paraelectrics, such as SiO$_2$, Ta$_2$O$_5$, Al$_2$O$_3$, and BCB, do not show phase transition behavior within expected microelectronic operation temperatures of -50 to +150°C. Figure 4 shows $k$ versus bias for Ta$_2$O$_5$ and BST. Many ferroelectrics exhibit a marked decrease in dielectric constant with increasing DC bias which may be used to advantage in fabricating a variable capacitor for tuning applications.
5. Dielectric Fatigue

Capacitors made with ferroelectric formulations can display a decrease of capacitance with time, number of charge cycles\textsuperscript{11}, and temperature\textsuperscript{45}. This phenomenon, called “dielectric fatigue” or “aging”, occurs due to crystallographic changes related to the relaxation of lattice strain energy\textsuperscript{42}. The rate of decay is logarithmic, of the form,

\[ k = k_0 - m \log t \]

The quantity “m” is sometimes expressed in percent per decade-hour. These effects are reversible with temperature and/or applied field and not all ferroelectrics exhibit them; PZT seems to show cycle fatigue but SrBi\textsubscript{2}Ta\textsubscript{2}O\textsubscript{9} does not\textsuperscript{45}. Paraelectrics do not show aging effects to any measurable degree. Figure 5 shows that, as a general trend, the breakdown field is lower for materials with higher dielectric constants, although even the high-k ferroelectrics exhibit breakdown fields of over 100 V for a 1 micron film (1 MV/cm)\textsuperscript{11,46}. Under high field conditions, the log of time to breakdown is proportional to applied field for ferroelectrics\textsuperscript{11,14}, as shown in Figure 6, while paraelectrics do not show this tendency.

6. Selection of Dielectrics for Integrated Capacitors

The general characteristics of these two classes of dielectrics are summarized in Table 2. The factors that influence the selection of a dielectric for integrated capacitor applications include the following factors.
Table 2. Comparison of paraelectric and ferroelectric dielectrics.

<table>
<thead>
<tr>
<th>Property</th>
<th>Paraelectrics</th>
<th>Ferroelectrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>2 - 50</td>
<td>up to 1000's</td>
</tr>
<tr>
<td>k vs. T</td>
<td>little dependence, -500 ppm/°C</td>
<td>can be highly dependent due to crystal phase transitions and ion mobility</td>
</tr>
<tr>
<td>k vs. frequency</td>
<td>little dependence</td>
<td>decreases significantly, typically above a few GHz</td>
</tr>
<tr>
<td>k vs. film thickness</td>
<td>no dependence since amorphous</td>
<td>highly dependent due to effects on crystal structure</td>
</tr>
<tr>
<td>k vs. bias</td>
<td>no dependence</td>
<td>decreases with DC bias</td>
</tr>
<tr>
<td>dielectric fatigue</td>
<td>none</td>
<td>k can decrease significantly with cycles and time</td>
</tr>
<tr>
<td>k vs. film structure</td>
<td>little or no dependence</td>
<td>film must be crystalline</td>
</tr>
<tr>
<td>care requirements</td>
<td>none</td>
<td>may require up to 700°C in O2</td>
</tr>
</tbody>
</table>

6.1. Performance Stability and Predictability

The dielectric constant of most ferroelectrics are a much stronger function of frequency, bias, temperature, time, film thickness, and film crystal structure than is the dielectric constant of paraelectrics.

6.2. Leakage

At equal values of specific capacitance in nF/cm², the high-k ferroelectrics will exhibit less leakage current than the lower-k paraelectrics by virtue of their thicker films.

6.3. Capacitor Size

This should be as small as possible to maximize the number of components per unit board area but, if the specific capacitance of the film is too high, it may be difficult to fabricate a low-valued capacitor, say 1 pF, in a size which is large enough to be easily or reproducibly defined by standard board-level photolithography. Figure 7 shows the length required for the side of a square integrated capacitor in mils to provide a given amount of capacitance for various dielectric materials.

![Figure 7. Sizes required for various integrated capacitor technologies.](image)

6.4. Film Integration

At present, almost all ferroelectrics require a high-temperature anneal in oxygen, at least 500°C, to attain the crystal structure necessary for high-k behavior. Paraelectrics do not require this and are, therefore, easier to integrate on some substrates.

The integration of capacitors into interconnect substrates is largely driven by three applications; decoupling of ICs from power supplies, analog functions such as those in RF/wireless devices, and termination of transmission lines. These capacitor characteristics affect their suitability for specific applications as described below.

6.5. Decoupling

The ubiquitous need for high-frequency decoupling capacitors to supply the transient current requirements of fast logic devices is well documented. Since the purpose of decoupling capacitors is to provide low-impedance for a single clock cycle, their most important characteristics are high capacitance and low inductance. The values of these capacitors will typically be among the largest on the substrate, from perhaps 20 to 1000 nF. Even higher capacitor values may be required for other energy storage applications. The inductance of an integrated capacitor is not a function of the dielectric material.

Tolerance is not important as long as they provide a minimum amount of capacitance. The resulting capacitance of the structure as a function of film composition, morphology, and thickness, as well as the capacitance as a function of frequency, bias, and time is not an issue as long as the minimum capacitance level is maintained under all operating conditions. Ferroelectric films or ferroelectric powders in epoxy generally exhibit less stable and predictable electrical performance in all of these respects than paraelectrics but their much higher dielectric constant can enable enough extra capacitance to be designed in from the start to make up for these shortcomings. Paraelectric materials are much more stable and predictable but cannot achieve the high capacitance of ferroelectrics.

Table 3 shows the length in mils required for the side of a square integrated capacitor to provide 100 nF. Film thicknesses of 2000 Å were chosen for most materials in this comparison since this thickness may be practically achieved by deposition (sputtering or CVD), anodization, and sol-gel, although deposited films may suffer from yield problems when they are this thin. From Table 3, low-k spin-on paraelectrics such as BCB or silica glasses result in unacceptably large structures while the higher-k anodized or deposited paraelectrics can provide 100 nF in areas which are larger than the footprint of a discrete but will fit in the real estate under a chip. A 1 micron layer of cured epoxy + ferroelectric powder on the high end of its k range has about the same specific capacitance as the highest capacitance thin film paraelectrics. Only thin film ferroelectrics can produce a decoupling capacitor that is smaller than a discrete of similar capacitance, but this technology has yet to overcome the problem of requiring a high temperature anneal, which precludes it from use directly on anything but ceramic substrates.
Table 3. Square plate size to provide 100 nF for various integrated capacitor technologies.

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>Dielectric Constant</th>
<th>Thickness (µm)</th>
<th>Specific Capacitance (nF/µm²)</th>
<th>Length of Side for 100 nF Cap (mils)</th>
</tr>
</thead>
<tbody>
<tr>
<td>spin-on BCB</td>
<td>2.7</td>
<td>2</td>
<td>1.2</td>
<td>3600</td>
</tr>
<tr>
<td>spin-on glass</td>
<td>3.7</td>
<td>1</td>
<td>3.3</td>
<td>2200</td>
</tr>
<tr>
<td>sputtered SiO₂</td>
<td>3.7</td>
<td>0.2</td>
<td>16</td>
<td>970</td>
</tr>
<tr>
<td>anodized Al₂O₃</td>
<td>9</td>
<td>0.2</td>
<td>40</td>
<td>620</td>
</tr>
<tr>
<td>anodized or sputtered Ta₂O₅</td>
<td>24</td>
<td>0.2</td>
<td>110</td>
<td>380</td>
</tr>
<tr>
<td>sputtered TiO₂</td>
<td>50</td>
<td>0.2</td>
<td>220</td>
<td>270</td>
</tr>
<tr>
<td>epoxy + ferroelectric paste</td>
<td>100</td>
<td>1</td>
<td>89</td>
<td>420</td>
</tr>
<tr>
<td>sol-gel or anealed ferroelectric</td>
<td>2000</td>
<td>0.2</td>
<td>8000</td>
<td>40</td>
</tr>
</tbody>
</table>

In order to provide 100 nF in a reasonably small area, the highest dielectric constants are called for and, since leakage is not of major importance, the thinnest films which provide acceptable yield may be used. A 1000 Å anodized Ta₂O₅ film would require 0.47 cm² to provide 100 nF and, under 5 V bias, would leak approximately 3 µA/cm². The resulting power loss due to leakage is then only about 7 µW which would not overheat the capacitor or overtax the power supply. A similar calculation for high-k ferroelectrics is even more favorable since the films can be thicker to give the same specific capacitance, which will result in less leakage per unit area, and/or the plates can be made smaller in area.

6.6. Analog Functions

In many analog functions such as RF/wireless, A/D conversion, filtering, and timing applications, required capacitor values range from about 1 to 100 pF, several orders of magnitude below those needed for decoupling. For these values, capacitor dielectrics which give high specific capacitance due to either high k or thin films should be avoided if the resulting plate size would be so small that precision would be unobtainable with board-scale lithographic resolution. For example, a 1 pF capacitor realized with 3000 Å of anodized Ta₂O₅ (about the thickest film that can be anodized) would be only about 1.5 mils on a side and the same capacitor made from 3 microns BaTiO₃ with a k = 2000 would be 0.5 mils across. Achieving 5% tolerance on a 1 mil x 1 mil capacitor plate requires a photolithographic tolerance of 0.025 mils or 0.6 µm. Thus, the use of thick layers of relatively low dielectric constant materials (<10) may be better for these low-valued components so that the resulting devices are large enough to be fabricated with sufficient dimensional tolerance to provide acceptable value tolerance. BCB and SiO₂ dielectrics are feasible dielectrics for this; 5 microns of BCB would require 18 mils x 18 mils to give 1 pF which requires 0.44 mils or 11 µm for 5% tolerance. Thicker films are also favored for most analog applications since leakage is very important and since higher yields will result. It may be possible to use the interlayer dielectric for these small capacitors thus saving a masking step.

In addition to problems with capacitor size, ferroelectrics are not as suitable as paraelectrics in these applications due to their lack of stability and predictability with respect to frequency, film thickness, film morphology, temperature, bias, and time. However, the decrease in k with frequency and bias for some ferroelectrics may be used as a tuning feature. Anodized films are very stable in all these respects but may have specific capacitances too high to be used in some low-value applications.

6.7. Termination of Transmission Lines

As system bus speeds increase, a significant number of lines must be terminated to avoid signal reflection. In CMOS systems, purely resistive termination may consume unacceptable amounts of DC power. Thus, an AC termination scheme consisting of series R/C is preferred. Over 2000 discretes are used on a Pentium III motherboard for termination5. Integrating R/C series terminators such as 50 Ω/100 pF or 100 Ω/50 pF into either passive networks or the motherboard itself, is highly desirable.

Exact tolerance of these capacitors is not critical, as long as they have a significantly lower impedance than the series resistor at the frequencies of interest. 5% tolerance is much tighter than what is required. Leakage is also not an issue for capacitors in R/C terminations as the expected leakage currents are very low compared to the drive capabilities of buffer outputs which are required to drive transmission lines in the 50 Ω range. Therefore, the choice of dielectrics for termination is driven by the same considerations for decoupling except that less capacitance is required.

7. Conclusions

Ferroelectric thin films have sufficient specific capacitance to be used as decoupling capacitors with advantageously small footprints. Since dielectric constant stability is not too important in this case, the ferroelectric thin films would excel in decoupling due to their much higher k values. The main problem with implementing ferroelectrics on organic substrates is the need for high annealing temperatures to form the high-k phases. Ferroelectrics are less suitable for analog applications, since their dielectric constant is usually a strong function of frequency, film thickness, crystallography, temperature, voltage, and time which also makes them less attractive for use in analog functions where high tolerance may be required. Also, many analog capacitors require values so low that, if made from high-k ferroelectrics, they may be too small for high-tolerance fabrication.

The high-k paraelectric materials exhibit specific capacitances that are just high enough for use in decoupling while still producing capacitors which are as small as a chip or the larger surface mount capacitors. Also, these dielectrics are currently more easily integrated into a wide variety of substrates. Leakage is not very important in decoupling so the lower limit on film thickness will be driven by defect density. Anodized films are more desirable than sputtered films since the former exhibits a lower fatal defect density which has a significant positive impact on yield with the large footprints required for decoupling. For analog functions,
thin film anodized paraelectrics are much more electrically stable than ferroelectrics but, again, may not be easily fabricated in high-tolerance values in the range of less than a few pF. BCB and SiO2 capacitors in micron-plus thicknesses would be sufficiently large to be easily fabricated with precision and have very flat dielectric constants with regard to frequency, film morphology, bias and operating environment. For termination capacitors, 50 - 100 pF are required and can be made at reasonable sizes with anodized paraelectric dielectrics. They could be made smaller with high capacitance density ferroelectrics, but the thin film resistor for the R/C terminator would also have to be scaled down and this places a lower limit on the achievable total R/C area.

Value requirements for integrated capacitors extend over six orders of magnitude from about 1 pF to 1 µF. For many applications, this entire range must be present on the same substrate with the upper end serving as decoupling capacitors and the lower end providing a variety of filtering, timing, coupling and A/D functions. It is difficult, if not impossible, for any single dielectric material and capacitor configuration to provide this entire value range without the resulting device being too large to be practical or too small to be fabricated with sufficient value precision. The best compromise might be to use either thin film anodized Ta2O5 or ferroelectric/epoxy composite for decoupling and, perhaps, termination and either BCB or SiO2 for other functions. If either of these two latter materials are present as an interlayer insulating material, it might be possible to use it as a capacitor dielectric also without having a additional deposition/patterning steps.

Acknowledgments

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