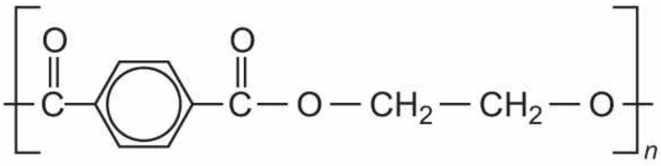
Chapter-4. Selection Issues of Substrate Material: Flexibility and Reliability

4.1 INTRODUCTION

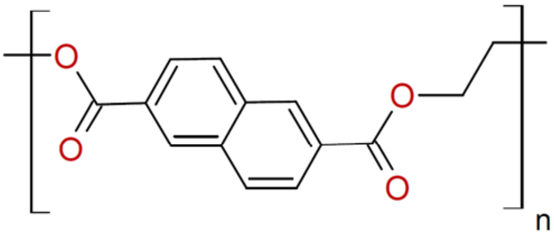
Low cost and flexibility are the two major advantages which the field of organic electronics offers when compared to the other existing technologies. The need for flexibility adds more emphasis on the mechanical stability of the device which was of least concern in the existing technologies. Since, flexible OTFTs are fabricated using heterogeneous materials in a layered structure, it is necessary to pay sufficient attention on the mechanical reliability aspect of the devices. Among the various layers, the role of a substrate becomes more prominent in determining the mechanical reliability of the overall device. A thin substrate (few hundreds of microns) is used as a base for the device. The choice of the substrate material is critical in determining the 'low cost' and 'flexible' aspects of OTFTs. Traditional substrates which include silicon wafers, metal foils, glass etc. are rigid and rarely possess properties like bendable, rollable and/or foldable. Therefore, it is a necessity to investigate and figure out the list of suitable materials, their properties and a structured framework to choose proper substrate material for the device.

In general, OTFTs which are reported in the literature are fabricated either on a silicon wafer or on a glass substrate. Study of such OTFTs fabricated on rigid substrates are aimed towards assessing: impact of device architecture, carrier transport and performance of organic semiconductor, gate dielectric and bias-stress effects on the OTFTs. The outcome from these studies provide insights into various factors that impact the device performance and parameters which can be altered to improve the performance. In such studies, which focuses on the performance improvement, it is observed that other than a few rudimentary studies on the OTFT behaviour when the OTFT is bent, very less emphasis is paid towards the reliability. However, to commercialize the technology, the *low cost, flexible* paradigm has to be incorporated into the fabrication. It would be possible only if one uses a polymer substrate. A few commonly used polymer substrate materials used for OTFTs include polycarbonate (PC) [133], [134], polyethylene naphthalate (PEN) [135], [136], polyethylene terephthalate (PET)[47], [137], [138], polyimide (PI) [139], [140] and polyether sulfone (PES)[141]. The chemical structures of these polymers are shown in Fig.4-1[49]. In addition to these commercially available polymers, other materials like cloth, rubber, paper etc. can also be used as substrate materials. However, such substrates suffer from poor uniformity, rough surface and above all large water absorption when operated in high humid environment [142]. Therefore, they are not so suitable for large scale commercial OTFTs and their use is restricted for specific applications. Polydimethylsiloaxane (PDMS) a commonly used polymer especially for stretchable applications doesn't suit the solution processable fabrication methods of an OTFT, since it has a tendency to absorb the solvents which results in swelling of the layer. Therefore, it is ruled out as a substrate material [143].

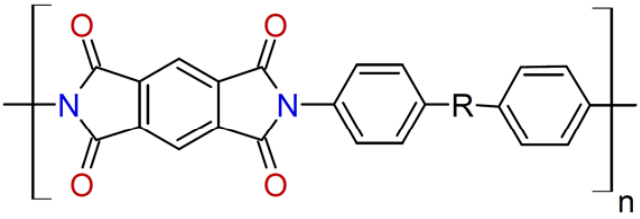
The field of organic electronics, has a unique advantage when it comes to the choice of materials used for fabrication. A rich wealth of materials which are well studied exists. It is also possible to tailor the properties of these materials to suit the purpose. Therefore, materials for OTFT has been extensively studied over the past two decades [21], [31], [42], [44], [49], [96], [144]. Existing studies on material issues are focused towards: finding high-mobility, air-stable organic semiconductors, polymer gate dielectric materials compatible with solution processing techniques and flexible electrodes. The reported results primarily focus on the electrical behavior of the OTFT expressed in terms of threshold voltage, mobility, subthreshold swing and I_{ON}/I_{OFF} ratio. The mechanical aspects of the design are often excluded from these studies. Therefore, a comprehensive understanding of the mechanical aspects and mechanical failures is missing. A probable reason for excluding mechanical aspects from the study could be due to the fact that conventional electronic devices, largely operate under normal conditions (no bending, no folding) and the mechanical design aspects are mostly restricted to static operation. While, flexible electronics demands dynamic mechanical analysis, this gap need to be explored.



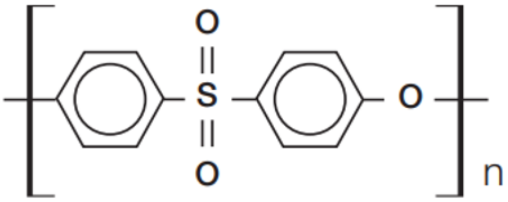
polyethylene terephthalate (PET)



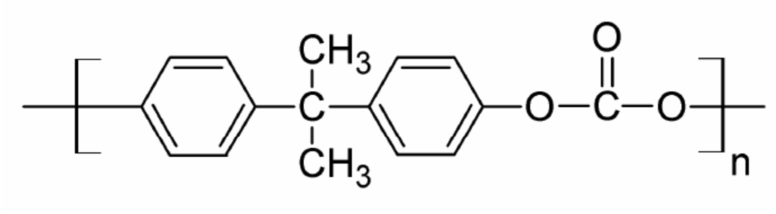
polyethylene naphthalate (PEN)



polyimide (PI)



polyethersulfone (PES)



polycarbonate (PC)

Figure 4-1 Chemical structures of a few frequently used polymer substrates in flexible electronic applications

Substrate, forms a base for the entire device and provides mechanical support. Moreover, it plays a crucial role in reliability of the device. Hence, this study is dedicated towards the study of material issues in substrate which could impact the stability of the device. In the subsequent section, mechanical, thermal, electrical along with the physical and chemical properties of polymer substrate are discussed and their relevance in the reliability of OTFTs is highlighted. Further, we apply the Multi-Criteria Decision Making (MCDM) technique for selecting a suitable substrate material for OTFTs. Tradeoffs exists while choosing a material. Therefore, it is not an obvious choice as to which of these materials suits the purpose better. Such problems, where there is a conflict, and a decision need to be made weighing the pros and cons of each alternative, MCDM could be used. Previously, it is established that MCDM materials can be used for material selection problems[109], [145]. Hence, we adapt the MCDM approach to find a suitable substrate material to improve the flexibility and realibility of an OTFT.

4.2 RELIABILITY ISSUES AND MATERIAL PROPERTIES

Reliability is an important feature for an OTFT. The reliability issues in OTFT go beyond the electrical reliability issues encountered in other TFT technologies. While the electrical aspects of reliability like hysteresis, bias and thermal stress effects persist, an additional aspect; mechanical reliability need to be considered for OTFTs. The niche of organic electronics; which is flexibility, demands for this additional requirement. Use of flexible substrate allows the OTFTs to conform to any shape while bending or folding alongside the advantage of low weight. In addition to this, use of flexible film as a substrate leads to the low cost mass production through roll processing. The need for flexibility eliminates the possibility of using glass, silicon substrates which are often used in other TFTs. Flexibility can be made possible by using either thin metal substrates or polymer substrates. A comparison of the various substrate materials available is shown in Table 4-1 [146].

Table 4-1 Comparison of various substrate materials used in TFT technologies

S.No.	Property	Metal Thin Films	Thin Glass	Polymer Substrates
1.	Surface Smoothness	Poor	Moderate	Good
2.	Dimensional Stability	Good	Good	Poor
3.	Processing temperature	High	High	Low
4.	Chemical Resistance	Fair	Good	Poor
5.	H_2O and O_2 Permeation	Low	Low	High
6.	Conformability	Good	Good	Good
7.	Bendable/Rollable	Poor	Poor	Goods
8.	Ruggedness	Good	Poor	Good
9.	Transparency	Poor	Good	Good
10.	Electrical Nature	Conductive	Insulator	Insulator

4.2.1 Thermal Stability

Substrate material need to withstand the high temperature processing steps involved in TFT manufacturing process. Although, the maximum temperature in TFT technologies is usually restricted below 300°C, it is a high value for the plastic substrates used in the flexible devices [147]. Therefore, thermal stability is an essential aspect to be investigated for a substrate. It is necessary to maintain the material characteristics when subjected to high temperatures. For plastics, beyond a certain temperature referred as glass transition temperature (T_g), the material becomes rubbery and soft, losing its glassy properties. Hence, it is a measure for the upper limit on temperature to which a polymer can be subjected without significant change in its properties. Therefore, for a substrate material it is necessary to have a high value of T_g for morphological stability.

4.2.2 Thermal Dimensional Stability

Good thermal dimensional stability is another important characteristic of a substrate material. Through good thermal stability it would be possible to realize large area devices and high resolution especially in the layered devices like OTFTs. Thermal dimensional stability ensures that the physical dimensions of the substrate doesn’t vary much when subjected to higher temperatures. A poor dimensional control could disturb the various critical dimensions of the OTFTs like channel length, width, spacing between two adjacent devices and hence impact the performance of the OTFT. Coefficient of thermal expansion (CTE) is a measure of the thermal dimensional stability. Most commonly used substrate materials made of silicon, aluminum thin films etc. have low CTE (<10 ppm/K). However, polymers have CTE on the higher side (>30 ppm/K). In addition to the dimensional stability aspect determined by the CTE of the substrate material, CTE mismatch between adjacent layers in the device also plays an important role. Minimization of the CTE is an important criterion. Else an unwanted thermal stress which could lead to an unwanted bending (deformation) in the device.

4.2.3 Thermal conductivity

Thermal conductivity refers to the ability of a material to conduct heat. Good thermal conductivity for a substrate ensures that the heat generated within the device (IC) can be quickly removed from the back of the substrate which is exposed to ambient air. Substrate usually is the thickest layer of the device and hence its thermal conductivity is an important aspect. The Joule heating effect generates enormous heat in the device. In case of an OLED and OTFT pixel driver circuitry collocated on the same substrate, the effective temperature on the top portion of the substrate where the devices are located can go as high as 80^{o}C. If this heat is not quickly transferred out of the system through the substrate, it accumulates and causes local heating. This could result in more trap states near the gate dielectric – semiconductor interface and thereby causing a shift in the threshold voltage of the device. A drop in the saturation current can also be observed due to mobility degradation when the temperature increases in the channel region. Therefore, its necessary to choose a polymer with good thermal conductivity as the substrate.

4.2.4 Surface Quality

Yield in TFT technology relies on the quality of interface between various layers. Therefore, surface quality is an important factor that needs to be considered while choosing a substrate material. Good surface quality improves the yield and longevity of the devices. While, a poor surface quality could either immediately render a device located over it to be defective (decreases in the yield) or manifest itself over a period to degrade the device characteristics (decrease in life time). In either case, it is a non-desirable effect. A measure of surface quality can be obtained by assessing the surface roughness and surface cleanliness through microscopic techniques. Rough surfaces, makes it increasingly difficult to deposit continuous thin film layers and could lead to discontinuities. Such discontinuities, could lead to increased grain boundaries in semiconducting layers, increased contact resistance near electrode region. Surface roughness is generally expressed as average roughness or RMS roughness. However, for polymer films, a plot of number of peak density Vs peak height could give a true measure of the surface smoothness. In addition to surface roughness, surface cleanliness is other important aspect. Since, fabrication of flexible devices is carried out at room temperature and in spaces which are not as clean as a *cleanroom,* surface contamination should be checked. Surface should be free from any contaminants (residue, dust or debris) which could have occurred while shipment (in case of as-received films), transfer (in case of grown substrates) and while handling. Over and above the cleanliness aspect, substrate should be examined for physical defects like scratches, cracks and pin holes. In case of non-clean surfaces, the substrates can be thoroughly rinsed in acetone and dried in a Nitrogen ambience. An optional, planarization layer could be deposited over the substrate to improve its quality. Planarization is achieved by depositing a very thin layer, which helps in smoothening the surface and toughen the surface and prevent scratches in subsequent processing steps.

4.2.5 Water vapor (H_2O) and Oxygen (O_2) permeation

Weatherability of substrates is an important measure for determining the stability of the device when operated in extreme weather conditions. Harsh environmental conditions could be: extremely hot or cold conditions, high humid environments and exposure to corrosive environment. Among these, humidity is a major concern for realistic scenario in which OTFTs are operated. Water vapor (moisture) and oxygen are two external contaminants which could lead to stability issues in OTFTs [148], [149]. Impact of moisture and oxygen on OTFTs stability is well studied and reported [150]–[152]. It is reported that long term exposure of OTFTs to oxygen and moisture leads to a shift in the threshold voltage [151]. Threshold voltage shift alters the I-V characteristics of an OTFT which could disturb the operation of the circuit. Special passivation layers which can act as barriers for oxygen and water could be deposited over the OTFTs limit the exposure [149].

Water Vapor Transmission Rate (WVTR) and Oxygen Transmission Rate (OTR) are a measure of the permittivity of a material for moisture and oxygen respectively. Not just in the case of OTFTs, organic photovoltaics which include organic solar cells and OLEDs have stringent requirements on the maximum permissible value for WVTR and OTR [148]. The permissible level for WVTR and OTR are 10^{-6} g/m^2/day and 10^{-3} cc/m^2/day. It is preferable to have these values as low as possible for the substrate to improve the longevity of the device.

4.2.6 Mechanical Properties

The mechanical robustness of flexible devices is influenced by the mechanical properties of the material: Young's (tensile) Modulus (Y), Shear Modulus (G) and bulk Modulus (K) [147]. Young's modulus, is a measure of the force required per unit area (applied normal to the load) to cause a fractional change (strain) in the length. Stress applied uniaxially can create deformation in the direction perpendicular to it, the negative rate of such deformation is described by Poisson ratio (v). For thin films, Young's modulus is the most relevant mechanical property and combined with Poisson ratio are sufficient to estimate the mechanical robustness of the structure. Flexibility, especially bending results in stress and induces strain in the devices. Strain in OTFTs is known to degrade mobility[153]. Therefore, attention has to be paid on the mechanical properties of the substrate material. In reality, thin devices are fabricated on a relatively thick substrate as shown in the Fig.4.2. The mechanical strain developed in the device when a bending of radius (R) is applied in terms of the Young's Moduli of the substrate (Y_S), film (Y_f) and their thickness d_s and d_f is given in Eq.(4.1) [154]. Thin substrates with low Modulus exhibit better flexibility and results in lesser strain on the device layer.

$$Strain_{surface}(\%)=\left(\frac{d_f+d_s}{2R}\right)\left(\frac{1+2\eta+\chi\eta^2}{(1+\eta)(1+\chi\eta)}\right)\times 100 \tag{4.1}$$

where, $\eta=(d_f/d_s)$ and $\chi=(Y_f/Y_s)$

When the Young's moduli of the substrate and film are comparable ($Y_f/Y_s \sim 1$), then the strain on the surface is approximately given by the relation shown in Eq. (4.2).

$$Strain_{surface}(\%)\approx\left(\frac{d_f+d_s}{2R}\right)\times 100 \tag{4.2}$$

Therefore, surface strain is a strong function of the device dimensions as shown in Fig.4.3. It can be observed that: as the thickness of the film becomes comparable to that of the substrate, more surface strain is generated. Moreover, the surface strain is a strong function of the ratio of individual Young's moduli of the film and substrate. If the film has a higher Young's modulus than the substrate less strain is observed.

Flexibility of a material is proportional to its Young's modulus. For a substrate of thickness d_s made of a material with Young's modulus Y and Poisson's ratio v the rigidity (inverse measure for flexibility) is given by Eq.(4.3). For substrates made of similar thickness, flexibility can be improved by choosing a substrate with lower value of Y since, Poisson's ratio for most polymer substrates are in the range of 0.3-0.4 [155].

$$Rigidity=\frac{Yd_s{}^3}{12(1-v)} \tag{4.3}$$

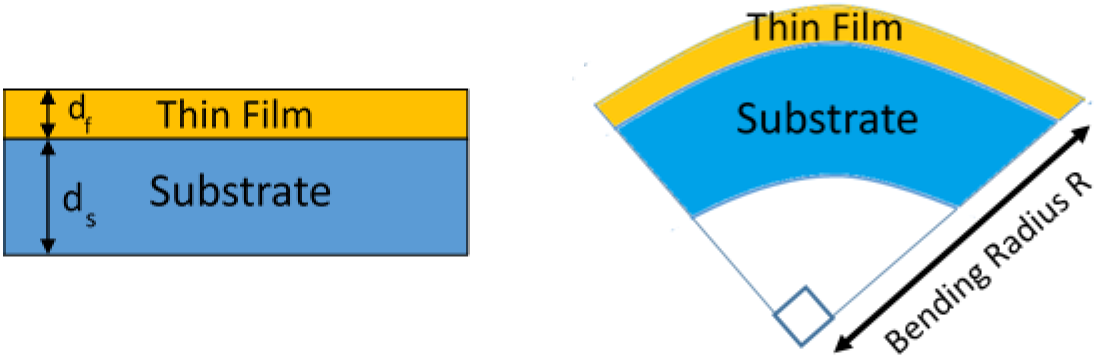


Figure 4-2 Bending of a substrate-thin film bi-layer

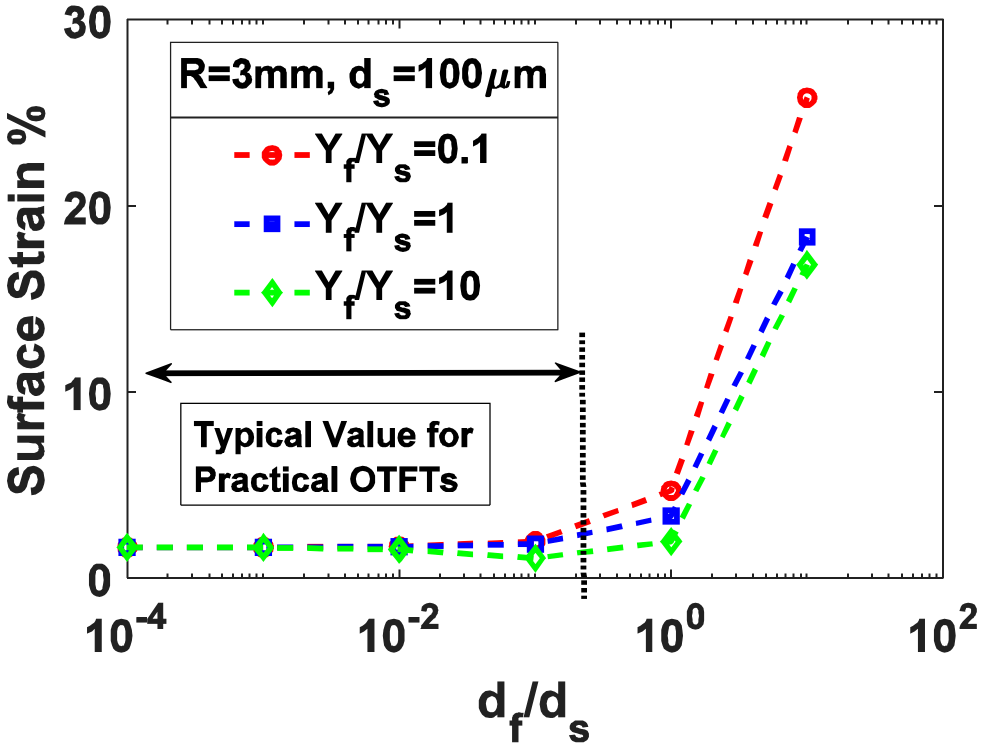


Figure 4-3 Surface strain as a function the ratio of thickness of the film to substrate as a function of various Young's moduli ratio for a given bending radius (R)

Optical properties like transparency (expressed in percentage), which measures the amount of light that can be transmitted by the substrate is an important parameter especially while choosing substrate for photovoltaic applications, where it is intended that light should be transmitted or absorbed. Higher optical transparency is required for such applications. Along with transparency, colorless substrates are preferred

4.3 MATERIAL SELECTION METHODOLOGY

Material selection problem can be addressed using the Multi-Criteria Decision Making (MCDM) frame work. Material selection is about making a choice from among the alternatives available based on a list of criteria. This transforms itself into the MCDM naturally. The *m* alternatives are various polymer substrates reported in the literature while the *n* criteria are material properties of interest which can influence the stability and longevity of the device. To begin with, a thorough literature review is conducted to identify most frequently used substrate materials in the field of flexible electronics and especially OTFTs. The material and their properties of interest are listed in Table 4.2. Where, *LB* indicates the Lower Boundary and *UB* indicates the Upper Boundary of the given parameter. Where, suitable data is not available on the *LB* and *UB* for any material the *LB* and *UB* are taken to be the same. Since polymers are molecular materials, their properties tend to vary over a given range. Hence it is important to consider the range of the values for the data rather deterministic values. An approach could be to choose the average value and perform the MCDM approach on deterministic data. However, such an approach could lead to false implications.

Table 4-2 Commonly used polymer substrates and their material properties

	Coefficient of Thermal Expansion CTE (ppm/K)		**Young's Modulus Y (GPa)**		**Glass Transition Temperature T_g (°C)**		**Thermal Conductivity (W/mK)**	
	LB[2]	**UB**[1]	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
PET[a]	20	80	2	4	68	85	0.15	0.24
PEN[b]	13	20	5	5.5	120	155	0.15	0.15
PI[c]	17	44	2	2.76	360	410	0.12	0.12
PES[d]	49	57	2.4	2.6	180	220	0.13	0.18
PC[e]	66	70	2.3	2.4	120	170	0.19	0.22

[1,2] Where, *LB* indicates the Lower Boundary and *UB* indicates the Upper Boundary of the given parameter. Where, suitable data is not available on the *LB* and *UB* for any material the *LB* and *UB* are taken to be the same.

The nature of the data in this case needs an MCDM approach that can handle the interval data rather than deterministic data. Therefore, the three techniques used in Chapter-3 MOSRA, VIKOR and TOPSIS can't be used in this case. We employ an extended version of TOPSIS proposed by Jahanshahloo et al. for this purpose [156]. The algorithm is briefly presented along with its application to the substrate selection problem.

4.3.1 Weight Normalized Decision Matrix

The first step is to obtain the weight normalized decision matrix. Normalization leads to elimination of the bias arising due to different range of values for each criteria and transforms them into the range [0,1]. After normalization, the quantities are dimensionless and can be freely operated upon. The weights assigned to each of criterion and the nature (benefit/cost) is presented in Table-4.3. *Benefit* criterion is the one which has to be maximum while *cost* criterion is to minimized. The expressions used for calculating the weight normalized criteria are given in Eq.(4.3)

$$\begin{aligned} n_{ij}^{l} &= w_j \frac{x_{ij}^{l}}{\sqrt{\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{u}\right)^2}} \quad \text{for } i=1,2,..\text{m and } j=1,2,..,\text{n} \\ n_{ij}^{u} &= w_j \frac{x_{ij}^{u}}{\sqrt{\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{u}\right)^2}} \quad \text{for } i=1,2,..\text{m and } j=1,2,..,\text{n} \end{aligned} \tag{4.3}$$

where, x_{ij}^{l} and x_{ij}^{u} are the lower bound and upper bound of the i^{th} alternative and j^{th} criterion and w_j is the weight of the j^{th} criterion. n_{ij}^{l} and n_{ij}^{u} are the weight normalized values of x_{ij}^{l} and x_{ij}^{u} respectively. The weight normalized decision matrix is shown in Table-4.4.

Table 4-3 Classification of the criterion and weight assignment based on their relative importance

Criterion	Nature of the Criterion	Weight
Coefficient of Thermal Expansion	Cost	0.2
Young's Modulus	Cost	0.3
Glass Transition Temperature	Benefit	0.3
Thermal Conductivity	Benefit	0.2

Table 4-4 Weight normalized decision matrix

	CTE		Young's Modulus		T_g		Thermal Conductivity	
	LB	UB	LB	UB	LB	UB	LB	UB
PET	0.0256	0.1022	0.0571	0.1142	0.0297	0.0371	0.0559	0.0895
PEN	0.0166	0.0256	0.1427	0.1570	0.0524	0.0677	0.0559	0.0559
PI	0.0217	0.0562	0.0571	0.0788	0.1572	0.1790	0.0447	0.0447
PES	0.0626	0.0728	0.0685	0.0742	0.0786	0.0961	0.0485	0.0671
PC	0.0843	0.0894	0.0657	0.0685	0.0524	0.0742	0.0708	0.0820

4.3.2 Calculation of Positive and Negative Ideal Solution

Positive and Negative ideal solution are hypothetical solutions for the problem. Positive ideal solution aims at maximizing the *benefit* criterion (B) and minimizing the *cost* criterion (C). While, the negative ideal solution aims at minimizing the *best* criterion and maximizing *benefit* criterion. Had the data be deterministic (LB=UB) then there would be a single positive ideal solution and one negative solution. Since the data is interval data, in this case there would be four possible ideal solutions. The expressions for calculating them are given in Eq.(4.4).

$$
\begin{aligned}
A_k^{+u} &= \left\lfloor v_1^{+u}, v_2^{+u}, \ldots, v_n^{+u} \right\rfloor = \left(\max\left(v_{ij}^{u}\right) \mid i \in B\right), \left(\min\left(v_{ij}^{l}\right) \mid i \in C\right) \\
A_k^{+l} &= \left\lfloor v_1^{+l}, v_2^{+l}, \ldots, v_n^{+l} \right\rfloor = \left(\max_{i \in B}\left(v_{ij}\right) \mid i \in B, k \in C\right), \left(\min_{i \in C}\left(v_{ij}\right) \mid i \in C, k \in B\right) \\
A_k^{-u} &= \left\lfloor v_1^{+l}, v_2^{+l}, \ldots, v_n^{+l} \right\rfloor = \left(\max_{i \in B}\left(v_{ij}\right) \mid i \in B, k \in C\right), \left(\min_{i \in C}\left(v_{ij}\right) \mid i \in C, k \in B\right) \\
A_k^{-l} &= \left\lfloor v_1^{+u}, v_2^{+u}, \ldots, v_n^{+u} \right\rfloor = \left(\min\left(v_{ij}^{l}\right) \mid i \in B\right), \left(\max\left(v_{ij}^{u}\right) \mid i \in C\right)
\end{aligned}
\tag{4.4}
$$

Table 4-5 Ideals' calculation for polyimide (PI) substrate material

	CTE	Young's Modulus	Tg	Thermal Conductivity
A^{+u}	0.01661079	0.0570943	0.17901939	0.08948934
A^{+l}	0.01661079	0.0570943	0.15718776	0.08948934
A^{-u}	0.10222025	0.15700933	0.02969102	0.04474467
A^{-l}	0.10222025	0.15700933	0.02969102	0.04474467

4.3.3 Separation Measure and Relative Closeness

Separation measure for each *alternative* from the ideal solutions obtained using Eq.(4.5) can be calculated using the Eq.(4.6). The four distances can be translated into a relative closeness measure. In this case the relative closeness measure in this case is an interval. The method for assessing the relative closeness is given by Eq.(4.6)

$$
\begin{aligned}
d_k^{+u} &= \left\{ \sum_{i \in B} \left(v_i^{+u} - v_k^{l}\right)^2 + \sum_{i \in C} \left(v_i^{+u} - v_k^{u}\right)^2 \right\} \\
d_k^{+l} &= \left\{ \sum_{i \in B} \left(v_i^{+l} - v_k^{l}\right)^2 + \sum_{i \in C} \left(v_i^{+l} - v_k^{u}\right)^2 \right\} \\
d_k^{-u} &= \left\{ \sum_{i \in B} \left(v_i^{-u} - v_k^{u}\right)^2 + \sum_{i \in C} \left(v_i^{-u} - v_k^{l}\right)^2 \right\} \\
d_k^{-l} &= \left\{ \sum_{i \in B} \left(v_i^{-l} - v_k^{l}\right)^2 + \sum_{i \in C} \left(v_i^{-l} - v_k^{u}\right)^2 \right\}
\end{aligned}
\tag{4.5}
$$

Relative closeness for k^{th} alternative $$Interval = \left[\frac{d_k^{-l}}{d_k^{-u} + d_k^{+u}}, \frac{d_k^{-u}}{d_k^{-l} + d_k^{+l}} \right] \qquad (4.6)$$

4.3.4 Comparison of Intervals and Ranking of the Alternatives

Comparison of intervals can be performed by calculating the *mid-point* and *half-width* of the interval. An alternative is ranked above the other if it has a higher value of *mid-point* when compared to the other alternative. In case if two alternatives have very close *mid-points* then, the one with minimum *half-width* has to be assigned a better rank.

4.4 RESULTS AND DISCUSSION

The five alternatives chosen: PET, PEN, PI, PES and PC, for the analysis are the most commonly used substrate materials in flexible electronics. The four criteria: CTE, Young's modulus, glass transition temperature and thermal conductivity are chosen based on the objective of enhancing the reliability aspect of the device. CTE, is important since it determines the dimensional stability of the device. In advanced OTFT devices where the device dimensions are being scaled down to make the device work faster, the critical dimensions of the device (channel length, width and device spacing) would be in the order of a few tens of nanometer. An average value of CTE for these materials is ~43ppm/K which would mean that for every 1^oC change in temperature, the substrate material of dimension 1cm would change by 430nm. This is a significant change and could be detrimental for the device operation. Therefore, a low CTE value is an essential property for a substrate. Young's modulus is a measure of the resistance a material offers for elastic deformation (reversible) under load. A high Young's modulus implicates that the material is stiff. Therefore, for a material to be flexible, we need to choose the one having lower Young's modulus. Along with the stiffness issue, a lower Young's modulus would also mean less surface strain as shown in Fig.4.4. Since, these two parameters need to be lower side for an ideal substrate material, they are categorized as *cost* criterion in Table-4.3.

Table 4-6 Separation measures for each alternative from the ideal solutions

Substrate material	d^{+u}	d^{+l}	d^{-u}	d^{-l}
PET	0.18442851	0.14238264	0.13385719	0.04665949
PEN	0.164993	0.14451175	0.09539843	0.08198737
PI	0.067219	0.05004826	0.19688061	0.15649146
PES	0.1233766	0.09812862	0.11960688	0.10061168
PC	0.14770229	0.12528531	0.10972157	0.09587291

Table 4-7 Interval calculation, mid-point and half width for each alternative and their ranks assigned

Substrate Material	Interval		Mid-Point	Half Width	Rank
	LB	UB			
PET	0.14659624	0.70808127	0.42733875	0.28074251	4
PEN	0.31486202	0.42118676	0.36802439	0.05316237	5
PI	0.59254711	0.95323364	0.77289037	0.18034326	1
PES	0.41406798	0.601825	0.50794649	0.09387851	2
PC	0.37243209	0.49612251	0.4342773	0.06184521	3

The other two criteria used for analysis; glass transition temperature and thermal conductivity are important in determining the thermal stability and longevity of the device. Glass transition temperature (T_g) limits the maximum temperature a polymer can be subjected to. Therefore, it is desirable to have a large T_g for the substrate. Once a polymer is subjected to temperatures larger than T_g it can undergo irreversible morphological changes like softening. Hence, for a substrate material, it is desirable to have high T_g. As the device dimensions' shrink, the current density and power density of the OTFT circuit goes high. This leads to self-heating effect in the channel layer. If the substrate material is a poor thermal conductor, then the problem of self-heating is further aggravated. Self-heating in OTFTs results in a shift in threshold voltage by creating interface states [157]. The shift can be reversible or irreversible. In either case, it is not desirable. To alleviate this problem, a good thermal conductor should be chosen as a substrate. Based on the discussion presented above, the criteria T_g and thermal conductivity are classified as *Benefit* criteria as shown in Table-4.3.

It would be rather unfair to claim that other than the four material parameters discussed so far, other properties can be neglected. It is to be noted that these four parameters are of utmost important in determining the reliability and longevity of the devices. Other parameters which are presented in section-4.2 like surface quality, WVTR and OTR are also equally important. However, on an average polymer materials have smooth surface in general and the exact quality has to be assessed through optical microscopic techniques for each substrate before the process begins. WVTR and OTR determine the permeability of water vapour and oxygen through the substrate. They are extremely important in determining the stability of organic devices. Although, OTFTs have less stringent requirements on WVTR and OTR when compared to organic photovoltaic applications (OLEDs and Organic solar cells), it is to be noted that polymer substrates are inherently poor barriers for moisture and gases. It is observed that the average value of WVTR and OTR for polymer substrates would be ~1g-m^{-2} per day and 1 cm^{3}-m^{-2} per day respectively. These values don't meet the stringent requirements of an OTFT: WVTR ~10^{-3} g-m^{-2}per day and OTR 10^{-4} cm^{3}-m^{-2} per day. Therefore, polymer substrates need an additional barrier layer which will make it impermeable for gas and moisture. Therefore, these parameters are not included in the analysis.

The weights assigned to the individual material parameters is shown in Table-4.3. Weights (w_j j=1 to 4) should be selected such that ($0 < wj < 1$ and $w_1+w_2+w_3+w_4=1$). Weights indicate the relative importance of each of the material properties on choosing a decision matrix. Since it is equally important to have a match of CTE between the adjoining materials in a layered structure to avoid stress generated while heating and cooling of the device. Therefore, minimizing CTE is given a slightly less priority when compared with Young's modulus. Similarly, T_g is assigned a slightly higher weight (0.3) when compared to thermal conductivity (0.2). This is due to the fact that polymers are inherently poor conductors unlike conventional substrates like silicon. Silicon substrates have thermal conductivity ~148W/mK [158] while the average of the polymer substrates considered in this case is ~0.16 W/m-K (maximum is 0.24 W/mK), which clearly indicates that the thermal conductivity is poor in polymers. Therefore, less emphasis is paid on the thermal conductivity.

The TOPSIS technique used here is a scalable technique. It can be extended to any number of criteria and any number of alternatives. Thereby facilitating a flexible framework. This technique provides a way to process the data and arrive at informed conclusions. The intellect of the user lies in identifying the alternatives, parameters and their impact on the expected objective and the relative importance of each of the parameters (weights). The outcome of the technique is a relative positioning (rank) of each alternative in comparison to other alternatives. Since, the data in this case is an interval data, two metrics: *mid-point* and *half-width* are employed to arrive at the final decision. The *mid- point* is an estimate of how close the solution is to a hypothetical ideal solution and *half*-width is a measure of the uncertainty in the estimation of this closeness. The user can interpret the data inspecting the *mid-point* and *half-widths* carefully to understand the meaning of *rank*.

The final results obtained from the interval TOPSIS approach is given in Table-4.7. From Table-4.7, it can be observed that PEN, PC and PES have very less uncertainty, while, PET followed by PI has maximum uncertainty. Looking at the *mid-point* in Table-4.7 it can be concluded that PI is the best possible solution followed by PES and PC. However, a pessimistic approach could lead to a conclusion that since the *half-width* is minimal for PES when compared to PI, PES could be ranked better than PI. Albeit, the top two ranks would still be shared by either of these two polymers. While making a final choice on as to which among these has to be used, other properties like stability when exposed to chemical solvents, tensile strength, elongation at break, economy, adhesion to deposited layers, wettability of the surface in case of solution processing, carbon footprint and electrical properties need to be considered.

4.5 CONCLUSION

The role of substrate material in determining the reliability of an OTFT are analysed. Important material parameters of the substrate and their influence on the stability issue are discussed. Five preferred polymer substrates: polycarbonate (PC), polyethylene naphthalate (PEN), polyethylene terephthalate (PET), polyimide (PI) and polyether sulfone (PES) are compared using four material properties: coefficient of thermal expansion (CTE), Young's modulus, glass transition temperature (T_g) and thermal conductivity are compared using interval TOPSIS technique. It is observed that among these substrates, PI fares better when compared to the other four alternatives and hence it is the best substrate material for an OTFT.