Chapter-3. Gate Dielectric Material Selection

3.1 INTRODUCTION

This chapter[1], deals with the gate dielectric material selection for an OTFT. Dielectric materials, play an important role in determining the overall performance of an OTFT [91]. A wide variety of materials which include: high-k inorganic materials like Al_2O_3[92], Ta_2O_5[93], Barium Strontium Titanate (BST), Barium Zirconate Titanate (BZT) [94], TiO_2, HfO_2[95] and transition metal oxides like ZrO_2 and Y_2O_3 [75] are investigated as gate dielectric material. However, deposition techniques used for these materials like: chemical vapour deposition (CVD), thermal evaporation, RF sputtering are expensive techniques and are not compatible with low cost plastic substrates used in OTFTs [96]. On the other hand, polymer dielectrics, which can be deposited using low temperature solution processing (LTSP) techniques and has good compatibility with organic semiconductor (OSC) is a preferred choice for gate dielectrics in OTFT. Among polymer dielectrics, poly-4vinylphenol (PVP)[97], poly-vinylalchohol (PVA)[98],[99], CYTOP[100], [101], poly-methylmethacrylate (PMMA)[102], [103], SU-8[104], benzocyclobutene (BCB)[105], poly-styrene[106], poly-acrylonytrile (PAN)[107] are used as gate dielectric materials. Polymers with –OH groups induce hysteresis in I-V characteristics of OTFT, which is an undesirable effect for OTFTs used in pixel driver circuits[108].

Material selection problems have been quiet often addressed using Multi-Criteria Decision Making (MCDM) approach [109]–[112]. MCDM techniques are intended to solve the problem of decision making in a scientific approach. Various approaches have been proposed to solve the problem of decision making, given: multiple conflicting criterion, set of alternatives and a goal. A MCDM problem can be characterized by its five main features: target, alternatives, preferences by the decision

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maker, criteria and outcome. In this work, three most widely used and accepted MCDM techniques: Multi Objective Optimization by Simple Ratio Analysis (MOOSRA), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Vlsekriterijumska Optimizacija I KOmpromisno Resenje (VIKOR) are used. Each of these techniques uses a different approach to find an optimal solution for a given problem. MOOSRA is a non-weighted technique in which each alternative is evaluated independent of the other by a ratio. TOPSIS uses vector normalization approach to rank the alternatives based upon their Euclidian distance from the positive ideal solution and negative ideal solution. While, VIKOR uses linear normalization and finds a compromise solution by comparing the group utility and regret from opponent of the alternatives.

In this work, we have applied the three MCDM techniques discussed above to solve the problem of material selection for gate dielectric in OTFTs. In section 3.2, various performance metrics and their dependency on the material parameters are presented. Section 3.3 presents a detail description and the rationale behind each MCDM technique chosen. Section 3.4 summarizes the results and an in depth analysis of the results.

3.2 PERFORMANCE METRICS OF AN OTFT

The key performance metrics of an OTFT include operation voltage, drive capability and reliability. Reduction in operating voltage, enhancement of drive current and improving the reliability are important for OTFT to emerge as a potential alternative for existing TFT technologies. These performance metrics and their dependence on intrinsic material properties of gate dielectric are discussed in the rest of this section.

Operation voltage of an OTFT is a strong function of its threshold voltage (V_T) and subthreshold swing (SS). While, V_T determines the minimum gate-source potential (V_{GS}) necessary to turn ON an OTFT, the SS determines the change in V_{GS} at V_{T} to effectively turn ON and turn OFF the OTFT. Generally, operating voltage is chosen to be three to five times the V_T. Therefore, threshold voltage and subthreshold swing need to be reduced to lower the operating voltage. Unlike MOSFETs, which operate in inversion region, OTFTs operate in accumulation mode. Hence, the concept of threshold voltage is quite different in case of OTFTs. Threshold voltage V_T, in an OTFT should account for the difference in work functions of the gate (metal) and semiconductor (Φ_{MS}) and the charge accumulated in the channel region (Q_{ch})[113]. In addition to this, V_T should also account for the interface traps (Q_{it}) in the channel region. The expression for V_T is presented in Eq.(3.1).

$$V_T = \Phi_{MS} + \frac{Q_{ch}}{C_i} + \frac{Q_{it}}{C_i} \tag{3.1}$$

where, C_i is the capacitance per unit area of the gate dielectric and is related to the gate dielectric constant ε_r and the insulator thickness t_i by

$$C_i = \frac{\varepsilon_0 \varepsilon_r}{t_i} \tag{3.2}$$

from Eq.(3.1) and Eq.(3.2), it can be concluded that by using a material with high dielectric constant, threshold voltage can be reduced.

Subthreshold swing (*SS*), is the inverse of slope of log(I_D) Vs V_{GS}. This is an important property of OTFT indicating how fast an OTFT can switch from ON to OFF state and vice-versa. An expression for subthreshold swing is shown in Eq.(3.3).

$$SS = \frac{\partial V_{GS}}{\partial \log I_D} = \frac{kT}{q} \ln(10) \left(1 + \frac{q^2 N^*}{C_i} \right) \tag{3.3}$$

Where, k is the Boltzmann constant, T is the absolute temperature, q is the unit charge of an electron and N^* is the effective trap density (per unit volume and energy) at the semiconductor-dielectric interface. From Eq.(3.3) it can be observed that an increase in C_i will reduce *SS*. In addition to this, reduction in the effective trap state density also helps in reducing *SS*.

From Eq.(3.1) and (3.3), it can be observed that both V_T and *SS* are influenced by interface trap density. Interface traps are a consequence of poor interface between gate dielectric and OSC. Therefore, a clean dielectric-OSC interface is necessary to reduce the interface traps, and hence improve V_T and SS [114]. The quality of dielectric-semiconductor interface in a bottom-gate structure, relies on how well the semiconductor layer is formed above the gate dielectric. To form a uniform, continuous and ordered semiconductor layer on the dielectric material using solution processing techniques, surface energy of the gate dielectric plays an important role. It is reported that gate dielectrics with low surface energy allows free flow of OSC material during deposition [115]. As a result, continuous, void free polycrystalline semiconductor film with tightly packed grains could be formed. This defect free OSC-dielectric interface can reduce V_T as well as SS. Therefore, to obtain low V_T and low SS, it is necessary to choose a gate dielectric material with large dielectric constant and low surface energy. However, when a high-k polymer dielectric forms a direct interface with the channel layer, dipoles in dielectric causes disorder in the channel layer. This results in trapping of charge carriers in channel. This is undesirable, because, it leads to an increase in the SS, degrades the mobility and also induces hysteresis in the I-V characteristics. As a result, it is preferred to choose a dielectric material, with moderate values for dielectric constant.

Another key performance metric of an OTFT is its driving capability. Driving capability refers to the amount of current which an OTFT can deliver in ON state. This is an important metric, especially when OTFT is used in pixel driving circuits for flat panel displays. Driving capability is directly related to the saturation current of an OTFT. Since, an OTFT can source maximum current while operating in saturation region. Current in the saturation region (I_{Dsat}) is empirically related to the mobility μ, aspect ratio W/L and gate dielectric capacitance C_i as follows.

$$I_{Dsat} = \frac{1}{2}\mu C_i \frac{W}{L}\left(V_{GS} - V_T\right)^2 \tag{3.4}$$

where V_{GS} is the potential difference between gate and source terminals and V_T is the threshold voltage. It can be concluded from Eq.(3.4) that to improve drive capability, one needs to lower V_T, increase field effect mobility, aspect ratio and C_i. Among these options, lowering V_T, increasing C_i have already been discussed earlier. Increasing aspect ratio, comes with a price of either large area (W is increased keeping L constant) or undesirable short-channel effects (L is decreased keeping W constant) and hence, rarely opted. While, large mobility helps in increasing the saturation current, it can be attributed to the surface energy of gate dielectric [115]. Low surface energy of gate dielectric layer allows the formation of complete first monolayer of OSC, and hence facilitates the deposition of such layers above it. The formation of first monolayer of OSC is crucial for the device performance, because the charge carriers in an OTFT are confined in the first few monolayers of the OSC [116]. In addition to this, microstructure and morphology of polycrystalline OSC film is dependent on the surface energy. Henceforth, it can be concluded that drive capability of OTFT, is a function of surface energy and dielectric constant of gate dielectric.

Apart from V_T and I_{Dsat}, reliability is another key performance metric. High reliability is desired for any electronic device. Deviation from expected I-V characteristics, structural damage are key issues that makes reliability an important factor to be addressed. From Eq.(3.2) it can be observed that by reducing thickness of dielectric material, C_i can be increased. However, a thin dielectric layer increases the gate leakage current, difficult to maintain uniformity from run-to-run and highly susceptible to electrical breakdown even at lower operating voltages. Since the electric field (E_i) across the dielectric layer is inversely proportional to its thickness.

$$E_i = \frac{V_{GS}}{t_i} \tag{3.5}$$

if E_i is greater than the breakdown field (E_{BD}) of the dielectric material, a catastrophic, irreversible failure occurs in the OTFT. To avoid this, dielectric materials with high value of E_{BD} is required.

Hysteresis is another common concern in OTFTs [117]. Hysteresis refers to the deviation in V_T with respect to the sweep direction of V_{GS}. Hysteresis is an unwanted phenomenon in OTFTs designed for pixel driving circuits, because it alters the threshold voltage and has an un-desirable impact on the display device [108]. Hysteresis in OTFTs is a consequence of bulk traps in gate dielectric layer, mobile ion impurities and the moisture absorbed in the gate dielectric layer [118][119]. To alleviate hysteresis, choosing a hydroxyl (-OH) free polymer as dielectric layer is recommended [118]. However, non-hydroxyl polymer dielectric based OTFTs too exhibit hysteresis due to their inherent nature of moisture absorption during their deposition. Hence, proper drying and heat treatment of the dielectric layer before the deposition of OSC helps remove the moisture and results in mitigating hysteresis effects in OTFT [119]. In addition to alleviation of hysteresis, annealing of OTFTs have shown improvement in mobility [120], [121]. Therefore, a good gate dielectric material should be capable of sustaining high temperature during annealing process to remove residual moisture. The maximum temperature to which a polymer can be subjected without altering its physical properties is referred as glass transition temperature (T_g). Hence, polymer dielectric materials with high T_g are preferred in OTFTs.

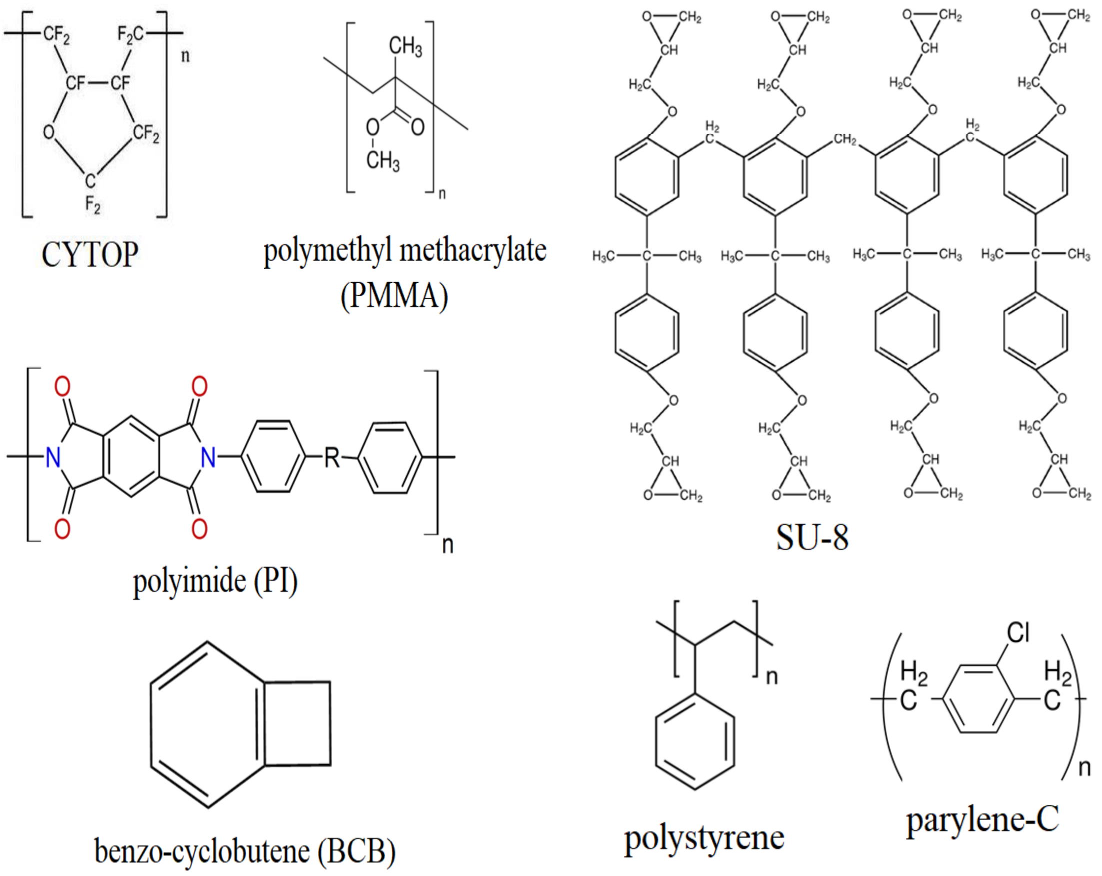
Therefore, for this study, operating voltage, drive capability and reliability are taken as performance metrics. The material indices which significantly impact these parameters are surface energy, dielectric constant, breakdown field and glass transition temperature. Hence, we use these material parameters as selection criteria and improvement of the performance metrics as the target while applying the MCDM approaches.

3.3 MATERIALS SELECTION METHODOLOGIES

Multi-criteria decision making (MCDM) approaches can be employed successfully for material selection in thin film transistors[109], [110]. A wide variety of techniques are available and well explored for MCDM problems. Among the available techniques, VIKOR, TOPSIS and MOOSRA are widely used techniques. In all these techniques, formulating a decision matrix is the starting step. Decision matrix D for m materials and n parameters is of size $m \times n$. Each row in the decision matrix D corresponds to a material and its parameters. The list of low-k polymer materials and the parameters chosen are presented in Table-3-1. Fig.3-1 shows the chemical structures of these polymers.

Table 3-1 List of polymer dielectric materials and their parameters

Material	Dielectric Constant (ε_r)	Surface energy (mJ/m^2)	Glass transition temperature (T_g °C)	Break down field (MV/cm)	Reference
CYTOP	2.1	19	100	2.5	[100]
Polyimide	3.3	55	320	1.5	[122][123]
SU-8	3.5	45.5	210	4.5	[124][125]
Polystyrene	2.6	40.7	100	4	[106][126][127]
BCB	2.6	39	350	3	[128]
PMMA	3.2	37	100	1.1	[129][130][131]
Parylene-C	3.1	36	150	2.2	[130][132][124][125]


CYTOP

polymethyl methacrylate (PMMA)

SU-8

polyimide (PI)

benzo-cyclobutene (BCB)

polystyrene

parylene-C

Figure 3-1 Chemical structures of the low-k polymer dielectrics used for gate dielectric material

3.3.1 MOOSRA

Multi Objective Optimization by Simple Ratio Analysis (MOOSRA) uses ratio of the benefit and cost criteria for decision making process. ‘Benefit’ criteria are those criteria whose value is desired to be as large as possible while ‘cost’ criteria are those for which, desired value is to be as small as possible. MOOSRA method is a non-weighted technique and is less sensitive to the large variations in the criteria. Also, each alternative is treated with equal priority. The solution to a given decision making problem using MOOSRA follows the following steps: (i) Problem definition and identifying the objectives, (ii) Identifying criteria and alternatives available, (iii) Formulation of decision matrix, (iv) Segregation of the criteria into cost and benefit categories and (v) Apply ratio system approach to rank alternatives.

The decision matrix D has m rows, each corresponds to an independent alternate solutions feasible for the problem, while, each of the n columns denote the criteria (objectives). For this case, decision matrix is a 7×4 matrix with 7 alternatives and 4 criteria which are listed in Table-3-1. Among these four criteria, dielectric constant, break down field and glass transition temperature are ‘benefit’ criteria while surface energy is the ‘cost’ criteria. The optimization is achieved by maximizing benefit criteria while minimizing cost criteria using ratio analysis. As a part of ratio analysis, following steps are performed.

$$\text{Decision matrix is given as } D=\begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1n-1} & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n-1} & d_{2n} \\ d_{31} & d_{32} & \cdots & d_{3n-1} & d_{3n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn-1} & d_{mn} \end{pmatrix}$$

In the decision matrix D each element d_{ij} denote the numerical value of j^{th} criteria for i^{th} alternative.

***Step-1*:** MOOSRA technique follows an internal normalization process. In this process, each column of decision matrix is normalized to make them dimensionless quantities so that they can be treated as numbers in further steps. Two alternate approaches are available for normalization as shown in Eq.(3.6) and Eq.(3.7).

$$d_{ij}^{*} = \frac{d_{ij}}{\sum_{j=1}^{n} d_{ij}} \tag{3.6}$$

$$d_{ij}^{*} = \frac{d_{ij}}{\sqrt{\sum_{j=1}^{n} d_{ij}^{2}}} \tag{3.7}$$

However, Eq.(3.7) may result in values greater than 1, but Eq.(3.6) results values in the range 0 to 1. This property will be quiet useful for simplifying the analysis further. In normalization step, nature of the criteria 'benefit' or 'cost' is not considered. Each alternative is compared against all other alternatives in the normalization process.

Step-2: In this step, overall performance score (s_i^{*}) of each alternative is calculated using expression shown in Eq.(3.8) To assess s_i^{*}, criteria are classified as benefit and cost criteria. Among the n criteria available if there are p benefit criteria and $(n-p)$ cost criteria, the performance score of i^{th} alternative is given by

$$s_i^{*} = \frac{\sum_{j=1}^{p} d_{ij}^{*}}{\sum_{j=p+1}^{n-p} d_{ij}^{*}} \tag{3.8}$$

Step-3: Arrange the alternatives in descending order based on the performance scores obtained from Eq.(3.8). The alternative on the top which has the highest performance score is the best possible solution to the given problem among the alternatives.

3.3.2 TOPSIS

Hwang and Yoon proposed Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) a solution for MCDM problems[112]. TOPSIS, unlike many other MCDM approaches is simple, has low computational complexity, intuitive and outputs a unique result by considering not just the ideal solution but also the non-ideal solution into account. It is a two-step process, where first a positive ideal and a negative ideal solution are assessed and distance for each alternative from them is calculated. The alternative which is at a larger distance from the negative ideal solution and closer to the positive ideal solution is considered the best possible alternative.

Following are the various steps involved in TOPSIS method (i) Formulation of the problem, (ii) Identifying alternatives and criteria, (iii) Formulation of decision matrix and assigning weights to criteria, (iv) Obtaining a positive ideal solution and a negative ideal solution, (v) Calculate, distance of each alternative from positive ideal and negative ideal solution and (vi) Ranking the alternatives based upon their relative closeness to ideal solution.

Step-1: For a given MCDM problem, prepare a list of viable alternatives and criteria. Formulate a decision matrix D whose size is $m \times n$. Each element of the decision matrix should satisfy the condition

$$d_{ij} \in \Re$$

Step-2: Assign weights to the criteria. The criteria can be benefit criteria (the more the better) or cost criteria (the lesser the better). The weight vector W is a row vector with each column corresponds to a criterion.

$$W = \begin{bmatrix} w_1 & w_2 & w_3 & \ldots\ldots w_{n-1} & w_n \end{bmatrix}$$

The weight vector W should satisfy the following properties.

$$w_i \in \Re \text{ and } \sum_{i=1}^{n} w_i = 1$$

Step-3: The decision matrix is normalized using the following relation. Normalization helps in transforming the criteria to dimensionless quantities. This feature helps us to treat these values as just numbers while comparisons and operations among the criteria.

$$d_{ij}^{*} = \frac{d_{ij}}{\sqrt{\sum_{j=1}^{n} d_{ij}^{2}}} \tag{3.9}$$

where $i = 1, 2, \ldots\ldots, m$ is the set of alternatives and $j = 1, 2, \ldots\ldots, n$ is the set of criteria

Step-4: The weighted normalized matrix is obtained by multiplying each row of the normalized matrix with the weight vector. $v_{ij} = n_{ij} \times w_j \ \forall \ i =$ 1 to m, j=1 to n.

Step-5: Obtain positive ideal solution $\left(A^{+}\right)$ and negative ideal solution $\left(A^{-}\right)$. Positive ideal solution, is the one in which benefit criteria is maximized while, cost criteria is minimized. For negative ideal solution, benefit criteria are minimized while, cost criteria are maximized.

Positive ideal solution

$$A^{+} = \left[v_1^{+} \quad v_2^{+} \quad v_3^{+} \quad \ldots\ldots \quad v_n^{+}\right] = \left\{\left(\max_i v_{ij} i \in B\right)\left(\min_j v_{ij} j \in C\right)\right\}$$

Negative ideal solution

$$A^{-} = \left[v_1^{-} \quad v_2^{-} \quad v_3^{-} \quad \ldots\ldots \quad v_n^{-}\right] = \left\{\left(\min_i v_{ij} i \in B\right)\left(\max_j v_{ij} j \in C\right)\right\}$$

where, *B* is associated with benefit criteria while, *C* is associated with cost criteria.

Step-6: For each alternative, calculate separation measure from positive ideal and negative ideal solution.

$$s_i^{+} = \left(\sum_{j=1}^{n}\left(v_{ij} - v_j^{+}\right)^{p}\right)^{1/p} \text{ for } i = 1,2,3\ldots\ldots, m \tag{3.10}$$

$$s_i^{-} = \left(\sum_{j=1}^{n}\left(v_{ij} - v_j^{-}\right)^{p}\right)^{1/p} \text{ for } i = 1,2,3\ldots\ldots, m \tag{3.11}$$

Usually, value of *p* is chosen to be greater than 1. The choice *p*=2, is commonly used and reduces the expression in Eq.(3.10) and (3.11) to Euclidian distance measure in Cartesian space.

$$s_i^{+} = \sqrt{\left(\sum_{j=1}^{n}\left(v_{ij} - v_j^{+}\right)^{2}\right)} \text{ for } i = 1,2,3\ldots\ldots, m \tag{3.12}$$

$$s_i^{-} = \sqrt{\left(\sum_{j=1}^{n}\left(v_{ij} - v_j^{-}\right)^{2}\right)} \text{ for } i = 1,2,3\ldots\ldots, m \tag{3.13}$$

Step-7: Obtain, relative closeness to ideal solution R_i

$$R_i = \frac{s_i^{-}}{s_i^{-} + s_i^{+}} \text{ for } i = 1,2,3\ldots\ldots, m \tag{3.14}$$

Based on the values of *R_i*, rank the alternatives in descending order. The alternative, which is on the top is the best possible among the alternatives.

3.3.3 VIKOR

Vlsekriterijumska Optimizacija I KOmpromisno Resenje (VIKOR) has its origin in Serbian which means multi-criteria optimization and compromise solution [111], [112]. It was proposed by Serafim Opricovic to solve MCDM problems with conflicting criteria. This technique involves in determining the best compromise solution among the given alternatives. It assesses each alternative against each and every alternative for a given set of criteria and weights to obtain two solutions. One, positive ideal solution and a negative ideal solution. Each alternative is assigned two scores: ‘group utility’ (majority score) and the ‘regret from opponent’ (minimum score). The final metric of decision is a linear combination of these two measures.

Following are the sequence of steps for applying VIKOR technique (i) Formulation of the problem, (ii) Identifying alternatives and criteria, (iii) Formulation of decision matrix and weight vector, (iv) Calculation of maximum group utility and regret from opponent and (v) Ranking alternatives based on the scores obtained from combination of outcomes in previous step.

Step-1: Formulate the decision matrix D of size $m \times n$ for m alternatives and n criteria. Identify and classify the criteria as ‘benefit’ and ‘cost’ criteria. For each criterion find out the positive ideal solution and the negative ideal solution using the following relation.

Positive ideal solution is obtained by

$$d_j^+ = \max d_j \text{ for benefit criteria } \min d_j \text{ for cost criteria where } j = 1,2,\ldots\ldots,n$$

Negative ideal solution is obtained by

$$d_j^- = \min d_j \text{ for benefit criteria } \max d_j \text{ for cost criteria where } j = 1,2,\ldots\ldots,n$$

Step-2: Assign weights to each criterion based on its relative importance. Weights assigned are subjective in nature and relies on the expertise of decision maker. The weights assigned should satisfy the criteria

$$w_i \in \Re \text{ and } \sum_{i=1}^{n} w_i = 1$$

Step-3: Calculate maximum group utility G_i and minimum regret from opponent R_i for each alternative

$$G_i = \sum_{j=1}^{n} \left(w_j \frac{d_j^+ - d_{ij}}{d_j^+ - d_j^-} \right) \text{ for } i = 1,2,\ldots\ldots,m \tag{3.15}$$

$$R_i = \max_j w_j \left(\frac{d_j^+ - d_{ij}}{d_j^+ - d_j^-} \right) \text{ for } i = 1,2,\ldots\ldots,m \tag{3.16}$$

Step-4: The VIKOR score Q_i of each alternative is obtained from G_i and R_i values

$$G^* = \min G_i \text{ and } G^- = \max G_i$$

$$R^* = \min R_i \text{ and } R^- = \max R_i$$

$$Q_i = v\left(\frac{G_i - G^*}{G^- - G^*} \right) + (1-v)\left(\frac{R_i - R^*}{R^- - R^*} \right) \text{for } i = 1,2,\ldots\ldots,m \tag{3.17}$$

The value v is called the voting parameter, where $0 < v \le 1$, and determines the strategy. $v > 0.5$ results in a solution that is dominated by the majority agreement while $v < 0.5$ results in a majority negative attitude. A compromise solution is obtained by setting $v = 0.5$.

Step-5: From the values obtained for Q_i, G_i and R_i, the alternatives are sorted in increasing order and ranked. An alternative is considered an "acceptable advantage" if among the alternatives ranked from A^1 to A^m based on Q_i value only if

$$Q(A^2) - Q(A^1) \ge (1/m - 1)$$

In addition to the above condition, if the alternative ranked A^1 has minimum value of *G* and/or *R* then the decision making outcome is considered to be stable.

3.4 RESULTS AND DISCUSSION

The decision matrix, *D* constitutes 7 alternatives and 4 criteria and is created using the material properties given in Table.3-1.This *D* will be the same for three material selection methodologies chosen. We shall apply each of the three techniques and try to find the best possible gate dielectric for an OTFT.

$$D = \begin{bmatrix} 2.1 & 19 & 100 & 2.5 \\ 3.3 & 55 & 320 & 1.5 \\ 3.5 & 45.5 & 210 & 4.5 \\ 2.6 & 40.7 & 100 & 4 \\ 2.6 & 39 & 350 & 3 \\ 3.2 & 37 & 100 & 1.1 \\ 3.1 & 36 & 150 & 2.2 \end{bmatrix}$$

3.4.1 MOOSRA Analysis

The normalized decision matrix for MOOSRA D_{MOOSRA} is calculated using Eq.(3.6) and is given as

$$D_{MOOSRA} = \begin{bmatrix} 0.013 & 0.070 & 0.075 & 0.133 \\ 0.162 & 0.202 & 0.241 & 0.080 \\ 0.172 & 0.167 & 0.158 & 0.239 \\ 0.127 & 0.150 & 0.075 & 0.213 \\ 0.127 & 0.143 & 0.263 & 0.160 \\ 0.157 & 0.136 & 0.075 & 0.059 \\ 0.152 & 0.132 & 0.113 & 0.117 \end{bmatrix}$$

The performance scores of each dielectric material is calculated using the ratio technique given by Eq.(3.8). Each dielectric material is ranked from 1 to 7, based on their performance score. Higher the performance score, better the rank (material with rank-1 is a better choice when compared to a material with rank-2 and so on). The performance scores and ranks for each alternative is listed in Table.3-2. CYTOP with a performance score of 4.457 is assigned *rank-1* followed by BCB (*rank-2*) and SU-8 (*rank-3*) with performance scores of 3.840 and 3.403 respectively. Since, the scores are distinct, a conclusive evidence can be drawn that CYTOP is the best polymer dielectric for an OTFT among the alternatives considered for the analysis. MOOSRA is a non-weighted technique, therefore a possible bias in the outcome of this technique due to the selective preference of the decision maker is nullified.

Table 3-2 Performance score of each polymer dielectric based on MOOSRA technique

Materials	Performance score	Rank
CYTOP	4.457	1
Polyimide	2.386	6
SU-8	3.403	3
Polystyrene	2.778	5
BCB	3.840	2
PMMA	2.138	7
Parylene-C	2.887	4

3.4.2 TOPSIS Analysis

The normalized decision matrix for TOPSIS D_{TOPSIS} is obtained from the relation given in Eq.(3.9).

$$D_{TOPSIS} = \begin{bmatrix} 0.269 & 0.179 & 0.176 & 0.323 \\ 0.423 & 0.517 & 0.564 & 0.194 \\ 0.448 & 0.428 & 0.370 & 0.582 \\ 0.333 & 0.383 & 0.176 & 0.517 \\ 0.333 & 0.367 & 0.617 & 0.388 \\ 0.410 & 0.348 & 0.176 & 0.142 \\ 0.397 & 0.339 & 0.265 & 0.284 \end{bmatrix}$$

The weight vector chosen is shown below

$$W = [0.2 \quad 0.4 \quad 0.1 \quad 0.3]$$

Each column in W corresponds to dielectric constant (0.2), surface energy (0.4), glass transition temperature (0.1) and the breakdown field strength (0.3) respectively.

The weights are chosen such that the summation rule 'sum of all the weights should be unity' is satisfied (0.2+0.4+0.1+0.3=1). Moreover, weights indicate the priorities and the relative importance of each criterion. Surface energy, is assigned the highest priority followed by breakdown field strength, dielectric constant and glass transition temperature. Surface energy has a significant impact on each of the three performance parameters: V_T, mobility and reliability. Its high significance is quantified by assigning a maximum weight (0.4) among the four criteria in W. Breakdown field strength, follows surface energy on the priority list. Since, it influences the reliability of the device. It limits the thickness of a gate dielectric. In case of an excessive voltage applied, which results in an electric field exceeding the one determined by the breakdown field strength, OTFT fails permanently. The damage caused due to dielectric breakdown is irreversible and catastrophic. Therefore, it is assigned a weight 0.3 in the weight vector matrix to quantify its significance. Assigning breakdown field strength second priority in comparison to surface energy could be justified by the fact that, good design practices ensure that the OTFT doesn't enter the breakdown region. Dielectric constant follows surface energy and breakdown field with a weight of 0.2. It can impact V_T and I_{Dsat}. A high dielectric constant can improve the I_{Dsat} and at the same time could have a negative impact of the V_T. Due to this conflicting nature, it is prioritized below the other two criteria: surface energy and breakdown field strength. Glass transition temperature, is related to the reliability aspect and has little impact on the performance metrics. Therefore, it has a lesser priority among the four material parameters presented. It is assigned a weight 0.1 in the weight vector.

$$\text{Weighted normalized matrix } V = \begin{bmatrix} 0.054 & 0.071 & 0.018 & 0.097 \\ 0.085 & 0.207 & 0.056 & 0.058 \\ 0.090 & 0.171 & 0.037 & 0.175 \\ 0.067 & 0.153 & 0.018 & 0.155 \\ 0.067 & 0.147 & 0.062 & 0.116 \\ 0.082 & 0.139 & 0.018 & 0.043 \\ 0.079 & 0.135 & 0.026 & 0.085 \end{bmatrix}$$

In TOPSIS technique, the suitability of an alternative to attain a specific goal is quantified as a measure of distance. The Euclidian distance pair $s^+$and s^- is assessed for each alternative using the expression given in Eq.(3.12) and Eq.(3.13). TOPSIS ranks alternatives based on the pair of distances rather a single metric. It accounts for how ideal solution is when compared to both extremities: positive ideal and negative ideal. An ideal solution is the one closest to positive ideal solution and farthest from the negative ideal solution. Hence, the final performance score R_i obtained using Eq.(3.14) is used for ranking the alternatives. The distance measures, performance scores and the rank assigned for each dielectric material is provided in Table.3-3.

Table 3-3 Rank based on TOPSIS analysis

Materials	**S^+**	**S^-**	**R**	**Rank**
CYTOP	0.096	0.146	0.603	1
Polyimide	0.179	0.052	0.225	7
SU-8	0.103	0.143	0.581	2
Polystyrene	0.098	0.125	0.562	3
BCB	0.098	0.106	0.519	4
PMMA	0.155	0.073	0.321	6
Parylene-C	0.116	0.088	0.431	5

If we compare the separation measures, it could be observed that CYTOP is the closest (s^+=0.096) to the positive ideal solution and it is also the farthest from negative ideal solution (s^-=0.146), therefore, it has the highest performance score (*R*=0.603). BCB and polystyrene have equal distance from the positive ideal solution (0.098) closely followed by SU-8 (0.103). However, SU-8 (s^-=0.143) is the second farthest alternative from the negative ideal solution after CYTOP. Therefore, SU-8 has a better performance score (*R*=0.582) than polystyrene (*R=0.562*) and BCB (*R=0.519*). Hence, SU-8 is assigned rank-2 due followed by polystyrene and BCB. Therefore, TOPSIS analysis indicates that CYTOP is the best possible dielectric material for an OTFT, followed by SU-8 and polystyrene.

3.4.3 VIKOR Analysis

The normalized decision matrix and the weight vector for VIKOR analysis remain the same as that of TOPSIS method. Unlike TOPSIS, which arrives at the best possible alternative by measuring its individual merit, VIKOR relies on the group utility *G* and regret from the opponent *R*. After attaining the positive ideal and negative ideal solution from the normalized matrix, *G* and *R* are calculated using Eq.(3.15) and Eq.(3.16) respectively. The VIKOR score *Q* of each alternative is obtained from Eq.(3.17). The results obtained and the relative ranking of each alternative based on the values of *G*, *R* and *Q* are shown in Table 3-4.

Table 3-4 Rank based on VIKOR analysis

Materials	G_i	**Rank based on** G_i	R_i	**Rank based on** R_i	Q_i **(*v=0.5*)**	**Rank based on** Q**i**
CYTOP	0.476	2	0.200	1	0.178	A1
polyimide	0.705	7	0.400	7	1.000	A7
SU-8	0.350	1	0.294	5	0.236	A2
polystyrene	0.514	4	0.241	4	0.333	A5
BCB	0.483	3	0.222	3	0.243	A3
PMMA	0.643	6	0.300	6	0.662	A6
Parylene-C	0.529	5	0.203	2	0.259	A4

The top two materials ranked $A1$ and $A2$ based on VIKOR score Q_i, are CYTOP and SU-8. The difference in the VIKOR scores of these materials $Q(A2)-Q(A1)=0.058$ which is less than 0.16 (1/6). But the VIKOR score difference between $A3$ and $A1$ is 0.065 which is also lower than 0.16. It can be observed that, dielectric materials CYTOP, SU-8 and BCB have not so distinguishable VIKOR scores but CYTOP has the best regret from opponent in comparison to BCB and SU-8. Therefore, from VIKOR analysis, the best material for gate dielectric in OTFT is CYTOP followed by SU-8 and BCB.

Henceforth, from the results obtained using these techniques, it could be observed that CYTOP is the best possible material to be used as dielectric in OTFT. SU-8 and BCB are the next best alternatives respectively. From Table.3-1 it can be observed that SU-8 has dielectric constant, break down electric field and glass transition temperature better than CYTOP but has a poor surface energy (low surface energy is desirable). As a result, OTFTs if realized using SU-8 instead of CYTOP may have poor mobility and large interface trap density. Large interface trap density not only increases *SS* but also V_T, as a result we see an increase in the operating voltage. SU-8 based OTFTs may also introduce a large hysteresis when compared to CYTOP based devices. Followed by SU-8 is BCB. The dielectric constant and breakdown electric field for BCB are better than CYTOP but not as good as SU-8. However, BCB has a better glass transition temperature when compared to both SU-8 as well is CYTOP. This property gives the device engineer an additional leverage while subjecting the device to high temperature steps like annealing. As a result, BCB based OTFTs are expected to be free from hysteresis effects which result from the residual –OH groups trapped in the dielectric layer. Moreover, BCB has a lower surface energy when compared to SU-8 but higher than CYTOP. Hence, using BCB instead of CYTOP in an OTFT has undesirable impact on mobility, *SS* and V_T due to the presence of trap states. This leads to an increase in operating voltage, reduced drive current and high probability of hysteresis. The reason, SU-8 precedes BCB as the suitable choice for gate dielectric is, because of its high dielectric constant and break down field. This facilitates the formation of a thin film with large dielectric constant there by increasing C_i. This increase in C_i will help offset the impact of increased trap state density on *SS* and V_T. The results obtained are in line with the experimental results reported in [59][60] which confirm the fact that use of CYTOP as a dielectric layer below the organic semiconductor improves the performance of an OTFT.

In addition to the above metrics, a few other intrinsic properties of the dielectric material might play an important role while choosing gate dielectric for OTFTs. These parameters, depend upon the target application. A few parameters could be Young's modulus, transmittance, water absorption, coefficient of thermal expansion, permeability to various gases, elongation at break and adhesion strength etc. Young's modulus and elongation at break are crucial for stretchable electronic applications like e-skin. Adhesion strength which is a measure of how strong a material can stick to its adjacent layers is another important parameter for stretchable electronics. Similarly, permeability to various gases will be crucial while designing an OTFT for sensor applications. Transmittance plays a crucial role in transparent electronic devices. An observation on these properties for the choices mentioned above CYTOP, SU-8 and BCB reveal that they are in similar range and doesn't differ in orders of magnitude. Hence, it can be stated that, intrinsic parameters not included in the material selection process may not significantly impact the choice of the dielectric material for OTFTs designed for pixel driving circuitry.

3.5 CONCLUSION

In this chapter, we have discussed and analyzed the problem of material selection for gate dielectric in OTFTs. Operating voltage, drive current and reliability are chosen as the performance metrics of OTFT. The aim is to maximize the drive capability, reduce the operating voltage and improve the reliability. The dependency of these performance metrics on the material parameters of gate dielectric is presented in this work. Based upon the analysis, four material parameters viz. dielectric constant, surface energy, glass transition temperature and electric breakdown field are identified as criteria for MCDM approach. Three MCDM approaches MOOSRA, TOPSIS and VIKOR are applied to select the best possible gate material for OTFT. From all these material selection methodologies, we can conclude that CYTOP is the best choice for gate dielectric material for OTFT. This is followed by SU-8 and BCB.