Journal of Electron Devices, Vol. 21, 2015, pp. 1811-1815

Journal of Electron Devices
www.jeldev.org

MATERIAL SELECTION METHODOLOGY FOR MINIMIZING DIRECT TUNNELING IN NANOWIRE TRANSISTORS

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Received 26-12-2014, online 21-01-2015

ABSTRACT

This paper presents a material selection methodology for selecting material for nanowire transistors using multiple attribute decision making (MADM) approach. Different possible materials investigated in this study are InAs, InSb, InP, GaAs, GaN, Si, Ge and carbon nanotubes (CNTs). The properties like band gap, band gap offset, thermodynamic stability, tunneling effective mass and crystal structures are taken into consideration and MADM approach is applied to select the best material. It is observed that silicon (Si) is the best material for minimizing direct tunneling in nanowire transistors out of all possible candidates. The outcome of this study is compared with the experimental findings. The match between the proposed work and experimental results confirm the validity of the proposed study.

Keywords: Field effect transistors (FETs), leakage, material selection, nanowire (NW)

I. INTRODUCTION

NANOWIRE transistors (NWFETs) have shown promising potential to revolutionize the area of electronic, optical, chemical and biological device application [1-3]. NWFETs are among the most promising means of overcoming the limits of today's planar silicon electronic devices due to architectural benefits. However, it has been observed that when the physical gate length of these devices is reduced to 5 nm, direct channel tunneling starts dominating the leakage current [4]. This tunneling current is a hindrance in the optimum operation of NWFETs. In order to provide enhanced performance in terms to minimum tunneling current it is important to choose the material so as to minimize the direct tunneling in the device.

The parameters which plays dominant role in determining the magnitude of tunneling current in nanowire transistors are band gap, effective tunneling mass, valence band offset, crystal structure and thermodynamic stability [4, 5]. The materials investigated are InAs, InSb, InP, GaAs, GaN, Si, Ge and CNTs [4, 6]. Each of the materials shows its own advantages and demerits. So it is very important to select the best possible material that can be used in nanowire transistors to enhance the device performance. In order to achieve this objective, Multiple Attribute Decision Making (MADM) Approach – Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [7] is used.

II. MATERIAL SELECTION METHODOLOGY

In this method, two artificial alternatives are hypothesized:

- Ideal alternative: One which has the best attributes values (i.e. max. benefit attributes and min. cost attributes)
- Negative ideal alternative: One which has the worst attributes values. (i.e. min. benefit attributes and max. cost attributes).

TOPSIS selects the alternative that is the closest to the ideal solution and farthest from negative ideal solution. In this method, the decision makers (DM) assign the weight priorities by using fuzzy linguistic variables which is an approximate way to represent natural words or sentences used in human judgment and perception. The fuzzy linguistic approach represents qualitative aspects as linguistic values by means of linguistic variables. Linguistic decision analysis transforms the linguistic description of the DM into a mathematical model to provide a flexible framework for solving decision problems.

The labels proposed for the weighting are the following:

W = {Essential; Very High; Fairly High; High; Moderate; Low; Fairly Low; Very Low; Unnecessary}.

The steps taken are as follows:

Step 1 – Normalize the decision matrix.

This step transforms various attribute dimensions into non-dimensional attributes, which allows comparisons across criteria. For standardizing, each column of decision matrix, is divided by root of sum of square of respective columns. Thus the element r_{ij} of the normalized decision matrix R is:

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} (X_{ij})^2}} \quad ..(1)$$

here r_{ij} is the normalized preference measure of the i^{th} alternative in terms of the j^{th} criterion.

Step 2 - Construct weighted standardized decision matrix by multiplying attributes weight to each rating**.**

With the set of weights $W = (w_1, w_2, \ldots, w_n)$ the weighted normalized matrix V can be generated as follows :

$$V = RW = \begin{pmatrix} w_1.r_{11} & w_2.r_{12} & \cdots & w_n.r_{1n} \\ w_1.r_{21} & w_2.r_{22} & \cdots & w_n.r_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ w_1.r_{m1} & w_2.r_{m2} & \cdots & w_n.r_{mn} \end{pmatrix} \quad \ldots(2)$$

where 'm' is the number of alternatives and 'n' is the number of criteria.

Step 3 - Determine ideal solution and negative ideal solution**.**

A set of minimum values for each criteria is Negative Ideal solution**.** The ideal solution A^* and the negative ideal solution A^- are:

$A^* = \{(\max v_{ij} | j \varepsilon J_1), (\max v_{ij} | j \varepsilon J_2), i = 1,2,3,\ldots,m\} = \{v_1^*, v_2^*, \ldots, v_n^*\}$

$A^- = \{(\min v_{ij} | j \varepsilon J_1), (\min v_{ij} | j \varepsilon J_2), i = 1,2,3,\ldots,m\} = \{v_1^-, v_2^-, \ldots, v_n^-\}$ ..(3)

Step 4 – Determine separation from ideal solution S_i* .

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2} \text{, for i = 1,2,3,\ldots,m.} \quad .(4)$$

Step 5 – Determine separation from negative ideal solution S_i^- .

$$S_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2}\ ,\ \text{for } i = 1,2,3,\ldots,m. \quad ..(5)$$

here, v_j^* and v_j^- are the values of the best and worst alternative in a particular criteria 'j'.

Step 6 – Determine relative closeness to ideal solution**.**

The relative closeness of an alternative A_i with respect to the ideal solution A^* is represented by:

$$C_i = \frac{S_i^*}{S_i^* + S_i^-},\ \text{where } 0 < C_i^* < 1 \text{ and } i = 1,2,3,\ldots,m . \quad (6)$$

Apparently an alternative A_i is closer to the ideal solution as C_i^* approaches to 1.

Thus C_i^*=1, if A_i=A^*, and C_i^-=0, if A_i=A^-.

Step 7 – Rank the preference order.

Now a preference order can be ranked according to the order of C_i^*. Therefore, the best alternative is the one nearer to the ideal solution and away from the negative ideal solution

III. RESULTS AND DISCUSSION

Various properties of different possible materials are shown in Table I [8]. The parameters relevant for determining effective tunneling mass have been divided in two categories; Band gap, valence band offset and thermodynamic stability have been placed in one category because their quantitative values are available. The comparison of these parameters is done in Table I. Effective tunneling mass and crystal structure have been placed in another category since they have been compared using ranks assigned on the basis of qualitative comparison. This comparison is presented in Table II [8]. The values mentioned are their weight ranks.

TABLE I
VARIOUS PROPERTIES OF DIFFERENT POSSIBLE MATERIALS

Materials	Band gap (in eV) at 300 K	Valence Band offset (in eV)	Thermodynamic stability (Enthalpy in kJ/mol)
InAs	0.36	0.35	Stable(-58.6)
InSb	0.17	0.67	Stable(-0.40)
InP	1.27	0.32	Stable(-88.7)
GaAs	1.43	0.35	Stable(-0.36)
GaN	3.4	0.7 $\pm$ 0.2 4	Stable(-0.23)
CNTs	0.6	0.34	Stable(-0.46)
Si	1.11	0.22	Stable(-0.99)
Ge	0.66	0.67	Stable(-0.97)

TABLE II
VARIOUS PROPERTIES OF DIFFERENT POSSIBLE MATERIALS AND THEIR WEIGHT RANKS

Materials	Tunneling effective mass weights rank	Crystal structure and their weights
InAs	5	Zinc blende (3)
InSb	3	Zinc blende (3)
InP	2	Zinc blende (3)
GaAs	6	Zinc blende (3)
GaN	4	Wurtzite (2)
CNTs	1	Honeycomb Crystal Lattice (1)
Si	8	Diamond Cubic (4)
Ge	7	Diamond Cubic (4)

Tunneling mass is inversely proportional to tunneling current. Diamond Cubic structure is most conducive in blocking tunneling current because of high tunneling mass, followed by zinc blende, wurtzite and honeycomb crystal lattice [9] For all the subsequent matrix computations, the sequence of properties adopted is: band gap, effective tunneling mass, valence band offset, crystal structure and thermodynamic stability.

In this technique, the ranks assigned to the parameters might vary slightly in the range of lowest ranked materials but the materials which are essential and highly ranked will never vary from person to person since the qualitative comparison is based on strong scientific foundations.

Step I: The first step in the TOPSIS method is to construct the normalized decision matrix.

$$R = \begin{bmatrix} 0.0863 & 0.3501 & 0.2454 & 0.3511 & 0.3501 \\ 0.0407 & 0.2100 & 0.4698 & 0.3511 & 0.2100 \\ 0.3044 & 0.1400 & 0.2244 & 0.3511 & 0.4201 \\ 0.3423 & 0.4201 & 0.2454 & 0.3511 & 0.1400 \\ 0.8149 & 0.2801 & 0.4909 & 0.2341 & 0.0700 \\ 0.1438 & 0.0700 & 0.3506 & 0.1170 & 0.2801 \\ 0.2661 & 0.5601 & 0.1543 & 0.4682 & 0.5601 \\ 0.1582 & 0.4901 & 0.4698 & 0.4682 & 0.4901 \end{bmatrix}.$$

Step II: The second step in the TOPSIS method is to assign weights to the various properties on which the various materials under consideration are being compared, and thus construct the weight matrix.

$$W = \begin{bmatrix} 3 & 5 & 4 & 1 & 2 \end{bmatrix}.$$

Step III: With the normalized decision matrix and weight matrix, the weighted normalized matrix can be generated as follows:

$$V = WR = \begin{bmatrix} 0.2589 & 1.7505 & 0.9816 & 0.3511 & 0.7002 \\ 0.1221 & 1.0500 & 1.8792 & 0.3511 & 0.4200 \\ 0.9132 & 0.7000 & 0.8976 & 0.3511 & 0.8402 \\ 1.0269 & 2.1005 & 0.9816 & 0.3511 & 0.2800 \\ 2.4447 & 1.4005 & 1.9636 & 0.3511 & 0.1400 \\ 0.4314 & 0.3500 & 1.4024 & 0.1170 & 0.5602 \\ 0.7983 & 2.8005 & 0.6172 & 0.4682 & 1.1202 \\ 0.4746 & 2.4505 & 1.8792 & 0.4682 & 0.9802 \end{bmatrix}$$

Step IV: From the above weighted normalized matrix, the value of separation variables was found out to be:

$$S_1^* = 0.1705 \qquad S_1^- = 0.3625$$
$$S_2^* = 0.0639 \qquad S_2^- = 0.2451$$
$$S_3^* = 0.3207 \qquad S_3^- = 0.1652$$
$$S_4^* = 0.3615 \qquad S_4^- = 0.2165$$
$$S_5^* = 1.0236 \qquad S_5^- = 1.0067$$
$$S_6^* = 0.1052 \qquad S_6^- = 0.2162$$
$$S_7^* = 1.1256 \qquad S_7^- = 1.2135$$
$$S_8^* = 0.1487 \qquad S_8^- = 0.1246$$

The ideal solutions are given in Table III. The ranks are assigned according to the '*C*' values. The material with the highest '*C*' value was given the best rank.

TABLE III
SOLUTION OF STUDY BASED ON TOPIS METHOD

Material	Solutions	Value of corresponding '*C*'	Rank
Si	C_7	0.8156	1
Ge	C_8	0.6325	2
GaAs	C_4	0.5126	3
InAs	C_1	0.4387	4
GaN	C_5	0.3562	5
InSb	C_2	0.3012	6
InP	C_3	0.2156	7
CNTs	C_6	0.0929	8

Table III shows that silicon possesses highest '*C*' value followed by germanium. So this shows that silicon (Si) is the most appropriate choice for minimizing direct tunneling in nanowire transistors, followed by germanium (Ge). In case speed of the device is the main criterion, GaAs can be used but for that one has to compromise on tunneling current.

The proposed outcome of this study was compared with the findings of Sylvia et.al [4]. The close match between the two studies validates the proposed methodology.

IV. CONCLUSION

A material selection methodology for minimizing direct tunneling in nanowire transistors was presented using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). It was observed that silicon (Si) is the best material for minimizing direct tunneling, followed by germanium (Ge). This finding is in agreement with the experimental findings proposed in literature.

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