Monte carlo optimization of multi-layer semiconductor material

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Abstract. At present, the demand for various types of semiconductor devices is increasing, and under the current situation of energy shortage, the improvement of the energy efficiency of semiconductors is the top priority for development of science and technology. For this purpose, this article establishes a physical model and mathematical optimization model for multi-layer semiconductors based on Monte Carlo Simulation. The developed model and corresponding equations are derived from thermodynamic theory and principles, and the computer programming is set up to get the optimal design of multilayer semiconductors through Monte Carlo simulation to achieve higher energy efficiency.

1. Introduction
The discovery of semiconductor materials can be traced back to Faraday's discovery of the special resistance change characteristics of AgS in the 19th century. Since then, scientists have continued to study this special material. The microelectronics industry has developed rapidly. It has successfully liberated human computing power in just a hundred years, and we have greatly benefited from it [1-5]. For example, emerging electric vehicles and hybrid vehicles rely on various power devices, such as IGBTs, FRD, MOSFET and SBD. At present, the challenges faced by silicon-based devices are mainly focused on power density, efficiency, reliability, and packaging. Further research on the application of SiC materials is needed[6-12]. Therefore, the development momentum of semiconductors will never stop here. Different devices and materials have different advantages and are suitable for different semiconductor devices. They are widely used in daily life, including large-scale microelectronics and computers, optical communication technology, photovoltaic cells, light-emitting diode lighting, etc[10-17]. Today, the focus of the development of semiconductor technology is to discover new semiconductor materials and explore new application, as well as to optimize existing microelectronic devices to increase the energy efficiency and performance to achieve high speed and high energy. The semiconductor industry has a wide range of applications and plays a fundamental role in the subsequent research and development of equipment. Therefore, society has paid more attention, and its development is extremely rapid. At present, the development and technological changes in various fields of semiconductor can be mainly divided into two points: the development of new semiconductor devices to explore new uses; the optimization of semiconductor processing technology and materials to achieve the goal of optimizing the efficiency of semiconductor devices. In this study, Monte Carlo method is used to get the optimal coefficient of performance of the semiconductor material.
1.1. Semiconductor energy efficiency

Semiconductor devices have come into our lives widely and have played an important role in technological progress [18-20]. Since its first appearance, semiconductors have greatly changed our lives. To take power semiconductor devices as an example, from the earliest diodes to the silicon-based IGBTs that can withstand thousands of volts [21-23], it has become the core component of high-speed rail and high-speed trains. However, any semiconductor device cannot achieve complete energy conversion, that is, it cannot achieve zero energy waste. Nowadays, with the increasingly serious energy problem, the world has fallen into a crisis of energy shortages, and electricity has become invaluable. It is predicted that in 2025, the electricity consumed in communications alone will exceed the total electricity consumed globally in 2011. These energies not only increase the expenditure of the government and the people [13], but also cause irreparable damage to the earth. Therefore, energy conservation and environmental protection have become a major direction of current scientific research [8, 21-23]. Compared with traditional power processing devices, power semiconductor technology and other semiconductor devices have been widely used for their high energy conversion rate and easy adjustment. Moreover, now that the power plant is built in the suburbs, the current needs to travel a long distance and go through several transformation steps to reach the residents' homes. Therefore, various semiconductor devices in the power supply system from power generation to electricity consumption, such as photovoltaic cells used for solar power generation, discrete devices used for large-scale high-voltage circuit rectification, and lighting appliances, light-emitting diodes will have high energy efficiency and low energy waste[24-30].

On the other hand, according to Joule's law, the energy loss during semiconductor operation, that is, wasteful work, will be released to the surrounding environment in the form of heat energy in the semiconductor, and excessive internal energy will affect the performance of the semiconductor [12]. Once the temperature rises, the number of current carriers in the semiconductor increases, the migration speed increases, and the obstacle to the current decreases; at the same time, the leakage current will increase and affect normal use. High temperature will also shorten the working life and further increase the failure rate of semiconductor devices, thereby increasing costs and wasting material resources. It is possible that in large-scale power facilities, because the temperature is too high and seriously affects the performance, additional cooling equipment is needed to ensure the normal operation of the semiconductor devices, which consumes a lot of additional energy. Therefore, we need to improve the efficiency of the semiconductor and reduce its power consumption.

1.2. Multi-layer semiconductor materials

In recent years, multilayer semiconductors have also become a trend in the semiconductor industry. The trend of miniaturization of electronic products requires smaller and denser semiconductor structures. This has led to a demand for semiconductor packages that have relatively low loss, lightweight structures, and support higher operating capabilities such as increased density, mobility, and service life. One way to address this need is multilayer semiconductor structures or 3D integrated circuits. Multi-layer devices can be used in military and commercial applications, including sensor processing, data recording, communications, and flight electronic equipment; they can also be used in portable consumer electronic products such as mobile phones and tablet computers. For example, a newly developed multilayer semiconductor sensor for acetone gas sensitivity. The device is designed with a stress regulating layer, a support layer, a metal layer, an insulator and a sensing film. The simulation results show that the device has good power consumption and thermo-mechanical reliability[21-24,26-27]. The scientists have also invented many methods for manufacturing and analyzing semiconductor stacked devices. For multilayer structures, low-quality and high-quality materials can be used. Someone proposed an extended Ebers-Moll model for simulating multilayer structures. The standard Ebers-Moll model of transistor structure is extended to accommodate more junctions. The photo-generated current, space charge region recombination current and carrier multiplication are added to the model [6]. Someone also proposed a method of layer-based device layout. This method groups equipment of continuous process layers in the same area or unit. The
continuous layer group is composed of sequentially arranged processing layers. The results show that the hierarchy-based layout method is effective[7].

2. Problem statement
The optimization of semiconductors must have certain restrictions, and no semiconductor device can be continuously optimized without restrictions. The limiting conditions of semiconductor work efficiency can be roughly divided into: material, application environment, Size of Semiconductor Device.

2.1. Material
First of all, the material of the semiconductor determines the basic properties of the semiconductor such as electrical conductivity, thermal conductivity, photosensitivity, and force sensitivity; therefore, the material is the first and the most important constraint. The cutting-edge research on improving the materials of semiconductor devices to improve energy efficiency has been mentioned above, but the development of new materials is very slow. Si has always been the main material of IC, and it is the result of multiple reasons. First, as an element whose content in the earth's crust is second only to oxygen, Si has abundant reserves, and its purification and crystallization are also very convenient, which can support the current huge consumption; secondly, the band gap of silicon crystal is 1.12eV, which makes Compared with other semiconductor materials, it is more resistant to high temperatures; finally, due to the purification and masking characteristics of the SiO2 film, the purification characteristics can greatly reduce the failure rate of semiconductor devices, and the mask characteristics can promote the planarization of the production of devices made of this material[4]. And the new type of semiconductor material, taking gallium nitride as an example, it is widely used and light-emitting diode lighting because of its large spectrum[15]. Therefore, the current third-generation semiconductor materials used in power semiconductor devices, optoelectronic semiconductor devices, and crystalline silicon widely used in the field of integrated circuits will not change in a short time. However, these materials have their own problems. For example, GaN has strong polarity, the electron transfer rate of Si is low, and the efficiency of light emission is low. These cannot be ignored in the subsequent modeling process[22].

2.2. Application environment
In addition, the impact of the environment on the efficiency of semiconductor work cannot be ignored. As we all know, the purpose of semiconductor production is to put it into use, and it must work in a daily environment, not an ideal environment for testing the ultimate efficiency of semiconductors in the laboratory. Therefore, when considering how to improve semiconductor efficiency, the environment must be considered. Temperature is the primary consideration. For example, the propagation speed of light in a semiconductor is a function of temperature[17]. Of course, in the process of studying semiconductor energy efficiency, people are more concerned about whether its resistance can meet the expected standard. The conductivity of a material is determined by two factors: the concentration of free carriers that can conduct current and its mobility (or degree of freedom of movement). Then, at a relatively low temperature (below 200K), the main scattering mechanism may be impurity scattering, and the carrier concentration is determined by the external doping. Therefore, the conductivity will increase with temperature. Another particularly interesting situation occurs at high temperatures (above 400K or higher), where the carrier concentration is inherent and the mobility is controlled by lattice scattering. At this time, the coefficient of resistivity change with temperature is different from before. (Green) Not only resistance, the band gap and various particle characteristics of semiconductors are closely related to internal energy[3]. In fact, temperature is the most important one of various environmental factors. After studying the temperature and single pulse dose dependence of the Therados semiconductor detector, it is found that when the temperature increases from 20°C to 32°C, the observed relative response rises in the range of 1.00 to 1.07. When the dose per pulse increases from When 9.8x10−6 is increased to 6.5x10−4Gy/pulse, the observed increase in relative
response ranges from 1.01 to 1.11. At this time, the performance of this LED illuminator shows a very significant temperature dependence. The effect of temperature on the semiconductor here is equal to the pulse dose[24]. In addition, the operating voltage of the semiconductor cannot be easily changed during use, so semiconductor devices also need to work in it. There have also been studies on voltage dependence: the resistance of the polycrystalline semiconductor grain boundary barrier model is determined by the thermionic emission on these barriers. Using several forms of defect state density in the boundary zone, the DC grain boundary current density as a function of the applied voltage is calculated. In all cases, currents are ohmic at low voltages; they can reach a quasi-saturation level at intermediate voltages, and they exhibit obvious bias dependence at high voltages[9].

2.3. Size of semiconductor device

The last, but still not negligible, restriction is the size of the semiconductor device. In the field where semiconductors are most used, the continuous improvement of integrated circuits and technology is the pursuit of extreme mini portability. With the integration of various electronic products in our lives into people’s daily communication, lightness and compactness have become market demands. Therefore, one should not blindly pursue energy efficiency, and make the device very bulky, ignoring the needs of society. The reduction will indeed change the various characteristics of microelectronic devices. For example, to simulate the excited electronic state of a semiconductor crystallite, this semiconductor crystallite is small enough (50 Ådiam), and its electronic properties are different from those of bulk materials. At this limit, the excited state and ionization process have similar molecular properties. However, the diffraction of bonded electrons by periodic lattice potential is still the most important part of the microcrystalline electronic structure. The redox potential of excess electrons depends on the size of the crystallites[5]. Of course, this is a reduction of the microscopic level, but it does change the properties of semiconductor materials. The geometric and size-dependent effects of metal-semiconductor contacts have been studied in a larger range to understand the origin of the significant contact effects on nano-wire devices. Because of the difference in the width of the depletion layer and the reduction effect of the image barrier, the difference in the width and height of the metal-semiconductor barrier between planar and NW devices is caused. This study shows that the formation of a higher doping concentration in the contact area depends on the size, so size control is necessary [18].

3. Mathematical model

The optimization of multi-layer semiconductor material is achieved with below mathematical model based on Monte Carlo Simulation including both objective function and constraints.

3.1. Objective function

The objective function is to get maximal value of the coefficient of performance (COP), which is equal to the ratio of heat transfer at the low temperature reservoir, \(Q_L\), to the work, \(W\). At the same time, the total work, \(W\) is the difference between heat transfer at the high temperature reservoir, \(Q_H\) and heat transfer at the low temperature reservoir, \(Q_L\).

\[
\max \quad COP = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L}
\]  

(1)

3.2. Constraints

The total work, \(W\) will be equal to the product of total voltage, \(U\) times the total current, \(I\) times the time, \(t\).

\[
W = UI \tau
\]  

(2)

As what can be seen from Figure 1 and Figure 2, it is assumed that the semiconductor material has \(\Psi\) pairs of P-N nodes in the direction of length and \(\Phi\) pairs of P-N nodes in the direction of width. It also has total \(Z\) layers in the vertical direction. Therefore, the coordinate pair of \((\phi, \varphi, \zeta)\) can be used
to represent the corresponding pair of P-N node and the coordinator elements of \((\phi, \varphi, \zeta)\) belong to the sets of \(\{1, 2, 3, \ldots, \Psi\}\), \(\{1, 2, 3, \ldots, \Phi\}\) and \(\{1, 2, 3, \ldots, Z\}\) respectively. It is assumed that the dimension sizes of length, width, height of each P node or N node of semiconductor material are \(L_{sx}, L_{sy}, L_{sz}\) and the dimension sizes of length and width of insulator material between P node and N node of semiconductor material are \(L_{ix}, L_{iy}\) and the dimension size of the whole semiconductor material.

\[
D_x = 2\Psi \times L_{sx} + (2\Psi - 1) \times L_{ix}
\]

(3)

\[
D_y = 2\Phi \times L_{sy} + (2\Phi - 1) \times L_{iy}
\]

(4)

\[
D_z = Z \times L_{sz}
\]

(5)

It is assumed that the heat transfer coefficient of semiconductor material is \(U_s\) and the cross section area is \(A_s\) while the heat transfer coefficient of semiconductor material is \(U_i\) and the cross section area is \(A_i\). The heat transfer rate is the product of heat transfer coefficient, heat transfer area and the temperature difference.

\[
Q_s = (U_s \times A_s + U_i \times A_i)(T_{sl} - T_{sh})t
\]

(6)

\[
Q_i = (U_i \times A_s + U_s \times A_i)(T_{sh} - T_{sl})t
\]

(7)

\[
figure 1. 3D Structure and dimension variables of multi-layer semiconductor material.
\]

\[
figure 2(top)/(bottom). Illustration of heat transfer in multi-layer semiconductor material. / related thermodynamic variables in the mathematical model.
\]

The corresponding temperatures and heat transfer relationship have been defined in below equations and the cold end of semiconductor material is regarded as 0-th layer and the hot end of semiconductor material is regarded as Z-th layer.

\[
T_{sl} = T_0
\]

(8)

\[
Q_s = Q_0
\]

(9)

\[
T_{sh} = T_Z
\]

(10)

\[
Q_i = Q_{Z+1}
\]

(11)
The total areas of top surface and bottom surface of the semiconductor material are equal to the sum of the total number of P node or N node, which is \(4 \Psi \Phi \), times the area of each P node or N node, \(Lsx \times Lsy\). The total areas of top surface and bottom surface of the insulator will be equal to the total area of material minus the total area of semiconductor material.

\[
A_5 = Lsx \times Lsy \times 4 \Psi \Phi \\
A_6 = Lsx \times Lsy - Lsx \times Lsy \times 4 \Psi \Phi \tag{12}
\]

For each P node and N node, the resistance is proportional to the length and resistance coefficient and it is inversely proportional to the cross section area. Therefore, Equation 14 and Equation 15 provide the calculation results of resistance for P node and N node.

\[
R_p = \rho_p \times \frac{Lsz}{Lsx \times Lsy} \tag{14}
\]

\[
R_n = \rho_n \times \frac{Lsz}{Lsx \times Lsy} \tag{15}
\]

The whole heat transfer rate is calculated based on the formula of Seebeck Effect.

\[
Q_L = \alpha d T_i t - \frac{1}{2} t^2 R t - K (T_H - T_L) t \tag{16}
\]

\[
Q_H = \alpha d T_H t + \frac{1}{2} t^2 R - K (T_H - T_L) t \tag{17}
\]

Equation 18 and Equation 19 can be derived from Equation 16 and Equation 17.

\[
W = Q_H - Q_L = \alpha d (T_H - T_L) t + t^2 R t = Ul \tag{18}
\]

\[
\alpha d (T_H - T_L) + t^2 R = Ul \tag{19}
\]

4. Case Study

According to Monte Carlo simulation, the variables in the variable list are calculated. Among them, all variables and parameters are uniformly distributed, and a large number of sample points are sampled, followed by optimization calculations. The construction of the model is entirely derived from the equations in the mathematical model part. Due to the large number of sample data points and in order to obtain the exact optimal value and to explore the exact relationship between the variables. Extracting the data obtained from the model operation results, we fit the relationship between several key variables and the final work efficiency and other dependent variables. The following relationships can be observed.

4.1. Change of hot/cold end temperature
The above Figure 3 gives an image of the relationship between $T_{SL}$ and COP. The points on the picture are directly derived from the results of model operations. It can be seen that $T_{SL}$ and COP show a very good linear decreasing relationship: $COP = -0.0006T_{SL} + 0.5816$, indicating that the efficiency of semiconductor refrigeration decreases with the increase of cold junction temperature. When fitting, $R$ is close to unity, SSE and RMSE is very small, indicating that the fitting effect is good. Similarly, there is the same linear relationship relationship between $T_{SH}$ and COP, which can be seen from Figure 4.

Figure 5 shows the relationship between $T_{SH}$ and QL. It can be seen that $T_{SL}$ and QL show a very good linear decreasing relationship: $COP = -0.0723T_{SL} + 70.08$, indicating that the heat absorption of the cold end of the semiconductor decreases with the increase of the temperature of the hot end. The fitting error is still very small.

Similarly, the relationship between the hot end temperature and several strain variables is opposite to that of the cold end temperature, and the coefficient of the function is also just the opposite. So we can conclude that the greater the temperature difference, the more conducive the semiconductor operation.

In Figure 6, the horizontal axis represents the cold end temperature, and the vertical axis represents the hot end temperature. In the chromaticity diagram, the intensity of the color indicates the magnitude of the strain value.

Figure 7 is the relationship between resistance and current, and a monotonous decreasing curve can be seen. Since it is not a pure resistance circuit, we believe that the relationship may not be a general inverse proportional relationship, so using 1 to 5 functions to fit the circuit respectively, the effect is not good. After fitting with an inverse proportional function, it is found that resistance and current...
basically follow an inverse proportional function relationship. This is consistent with \( \alpha I (T_H - T_L) + I^2R = UI \), and shows that the temperature difference has a small effect.

4.2. Change of thermal property coefficient

It can be observed from Figure 8 and Figure 9 that the two proportional relationships indicate that the larger the semiconductor thermal conductivity, the higher the work efficiency, and correspondingly, the more heat is absorbed from the cold end.

4.3. Change of seebeck coefficient

It can be observed from Figure 10 and Figure 11 that \( \alpha \) has a decreasing relationship with efficiency and heat absorption, indicating that the smaller the Seebeck coefficient, the higher the efficiency, the more heat absorption, and the better the work effect. When the Seebeck coefficient decreases, it can save energy, reduce current and work.

5. Conclusions

This research project mainly optimizes multi-stage semiconductor refrigeration, establishes a mathematical model, and uses the Monte Carlo method for numerical simulation. Through simulation, we have obtained the relationship between the effects of various variables on the semiconductor efficiency: when the temperature difference is constant, the efficiency and the heat absorption of the cold end decrease with the increase of the temperature of the cold and hot end, and the work is independent of the temperature—control the temperature of the other end When constant, the efficiency and cold-end heat absorption decrease with the increase of the cold-end temperature, and the work increases accordingly; while changing the hot-end temperature, the relationship is just the opposite and according to the chromaticity diagram, we can observe that the greater the temperature difference, the higher the efficiency, the greater the heat absorption, the smaller the current, and the smaller the work done, which is consistent with the observation: the electrical resistance and thermal conductivity are also positively related to efficiency, and the Seebeck coefficient is negatively related
to efficiency. Therefore, it can be seen from the research results that in order to improve the working efficiency of the semiconductor, increase the heat absorbed by the cold junction, and reduce the work done, the following suggestions can be given: increase the temperature of the cold and hot section, increase the semiconductor resistance, thermal conductivity, and reduce Seebeck coefficient.

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