

# Characteristic analysis and simulation of a Cu-graphene hybrid nanointerconnect under different Drude models

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**Abstract.** It is well known that the ultra thin barrier layer around the Cu nanointerconnect has a great impact on its performance. Currently, graphene is the thinnest two-dimensional material. Cu-graphene hybrid nanointerconnects can significantly advance the potential of integrated circuit technology. In this article, we put a monolayer graphene on the top, left and right sides of a Cu nanointerconnect. Graphene adopts three Drude models, namely, the Drude model obtained by simplified Kubo formula, the Drude-Lorentz model, and the Drude model derived from Boltzmann equation. We use CST to simulate the voltage-current variation and propagation delay characteristics of a Cu-graphene hybrid nanointerconnect are observed under three Drude models and compared with a Cu nanointerconnect. Finally, the Drude model of graphene which is derived from the Boltzmann transport equation can minimize the voltage of the Cu nanointerconnect and reduce the propagation delay of the two ports of the Cu nanointerconnect.

**Keywords:** a Cu-graphene hybrid nanointerconnect; a Cu nanointerconnect; Drude model; propagation delay; CST.

## 1. Introduction

Integrated circuits, also known as IC. It integrates many commonly used electronic components, such as resistors, capacitors, transistors, and the nanointerconnects which are between these components, through a semiconductor process [1]. At the beginning, people studied analog integrated circuits, but they found that traditional analog integrated circuits are very time consuming and it also has certain requirements on the size of components. Therefore, digital integrated circuits have gradually replaced analog integrated circuits because of their stability, ease of design, low cost and programmability. At present, people have closely linked semiconductor devices and digital integrated circuits, and achieved a lot of results. In recent years, with the continuous development of semiconductor technology, interconnects have gradually become a more and more important research direction. In this paper, we mainly introduce some characteristics of a Cu nanointerconnect and a Cu-graphene hybrid nanointerconnect, and compare and analyze them.

With the in-depth study of semiconductor devices, the resistivity of Cu nanointerconnects becomes larger with the increase of technical nodes, and its transmission performance becomes worse, the propagation delay increases, more heat is generated, crosstalk noise is increased, and other negative effects are generating, so the Cu nanointerconnects gradually cannot meet the needs of the increasing current density. Graphene is a good solution to this problem, due to the two-dimensional characteristics of graphene, long um class mean free path, huge electrical conductivity, graphene has the ability to promote the development of integrated circuit, lower signal latency, faster data transmission speed, so that integrated circuits become more reliable [2]. There have been a lot of research on graphene, such as the parallel interconnection of graphene-carbon nanotube bundle nanointerconnects and the horizontal interconnection of graphene-carbon nanotube nanointerconnects; vertical multilayer graphene nanointerconnects and parallel multilayer graphene nanointerconnects [3]; Cu-graphene hybrid nanointerconnects. Assuming that the Cu nanointerconnect extends along the y direction, then multilayer graphene is laid on both the x and z directions of the Cu nanointerconnect, and the electrical properties of the Cu-graphene hybrid nanointerconnect are studied based on equivalent single-conductor transmission lines [4]. Research shows that laying graphene on Cu nanointerconnects can effectively solve the problem of Cu nanointerconnects, reduce the propagation delay, reduce the crosstalk effect, and reduce the loss of Cu nanointerconnects. It solves the problem of Cu-graphene hybrid nanointerconnects well.

Cst is a 3D electromagnetic field simulation software, which is a comprehensive, accurate and highly integrated professional simulation software package for 3D electromagnetic, circuit, temperature and other aspects [5]. In this paper, we mainly use the 3D electromagnetic module to observe the voltage change and propagation delay by adding a gaussian current source to the nanointerconnect.

In this paper, we select three different graphene Drude models, graphene is set up as a two-dimensional or an ultra-thin structure. For the Drude model obtained by simplified Kubo formula and the Drude model obtained by boltzman equation, the simulation of a monolayer graphene is carried out according to the impedance boundary conditions. For the Drude-Lorentz model, the dielectric constant of graphene is introduced into cst. By comparing the results obtained from the three Drude models with a Cu nanointerconnect, the graphene Drude model derived from boltzman equation can greatly reduce the resistivity of Cu nanointerconnects and the propagation delay of nanointerconnects.

## 2. Analysis of a Cu nanointerconnect

In the integrated circuits, the nanointerconnect plays an important role, it connects the components and the whole circuit together, so the quality of the nanointerconnect has a great relationship with the device performance and the yield of the chip. With the development of integrated circuits, metal copper has replaced the original aluminum nanointerconnect due to its excellent properties such as lower resistivity, higher thermal conductivity and melting point, and stronger anti electromigration. Metal copper has always been used as the nanointerconnect of integrated circuits and has been widely studied [6]. According to the manufacturing size of ITRS-2013 [7], the resistance, inductance and capacitance of the Cu nanointerconnect were calculated using the equivalent model of the Cu nanointerconnect at the technical nodes of 14nm,22nm and 32nm, and the step response simulation of the input voltage of the equivalent circuit model was carried out to obtain the transmission delay of the Cu nanointerconnect. The results show that when the length of Cu nanointerconnect is fixed, the transmission delay increases gradually with the decrease of the process size. When the manufacturing size is unchanged, the transmission delay will enter the *nm* level with the increase of the length of the Cu nanointerconnect [8]. Then, we will simulate the Cu nanointerconnect in the cst.

### 2.1 Voltage analysis of a Cu nanointerconnect

Voltage is a good indicator to compare the Cu nanointerconnect with the Cu-graphene nanointerconnect under different Drude models. The change of resistivity between the Cu nanointerconnect and the Cu-graphene nanointerconnect can be directly observed by analyzing the voltage variation.

We assume a Cu nanointerconnect that the simulation frequency is in the range of 0 – 50GHz, the dimension of the Cu nanointerconnect is  $10nm \times 10nm \times 10um$ , and is discretized into a uniform  $10 \times 8 \times 20$  grids. We still assume that the Cu nanointerconnect extend along the y direction, the four sides along the x directi-on and the y direction, we set PMC as the boundary condition, other sides along the z direction, we set PEC as the boundary condition. A graaussian current source  $j_i$  is added in the z

direction,  $j_i = - (t - t_0)exp \left[ - \left( \frac{t-t_0}{\tau_s} \right)^2 \right] \times 10^{16} A/m^2$ , where  $t_0 = 4\tau_s$ ,  $\tau_s = 2 \times 10^{-11}s$ .

We can analysis that the difference between the current and voltage drop of the Cu nanointerconnect is 1000 times, which is consistent with the resistance R calculated from the Cu nanointerconnect size. The simulation result is consistent with the actual results.

## 2.2 Propagation Delay analysis of a Cu nanointerconnect

For the integrated circuits, propagation delay is also an important characteristic of nanointerconnects. The Cu nanointerconnects now replace the aluminum nanointerconnects, reducing the transmission delay by about 40%. The smaller the propagation delay of the interconnect, the better the performance of the integrated circuit.

Then, we take a rectangular current source which has a 50 ps rising time and add it to the Cu nanointerconnect. Using cst simulation, we use the same steps like 2.1 chapter, but we set a new voltage monitor and also place it along the z direction at the other port of the Cu nanointerconnect. The two sides along the x direction, we set open (add space) as the boundary condition and another two sides along the y direction, we set PMC as the boundary condition, along the z direction, we set PEC as the boundary condition at other two sides. We can observe the propagation delay between the two ports of the Cu nanointerconnect. The time difference between the two port voltages is the propagation delay.

$$j_i(t) = \begin{cases} 1.09 \times 10^{10} \text{ A/m}^2 & 7.5ps < t < 57.5ps \\ 0 & \text{otherwise} \end{cases} \#(1)$$

It can be seen from the simulation results that the maximum voltage of the Cu nanointerconnect is about 42nV and the propagation delay is about 2.251ps. Although the propagation delay of Cu nanointerconnects is already at ps level, we also need other materials to continue reducing the propagation delay of the nanointerconnect to improve the integrated circuits (IC). Researchers also have studied the propagation delay characteristics between multilayer graphene nanointerconnects and carbon nanobundle nanointerconnects, and have achieved some results. Some nanointerconnects can significantly improve the propagation delay, while others will make the propagation delay becomes worse than before.

Although the various properties of Cu nanointerconnects have been greatly improved compared with aluminum interconnects, the resistivity of Cu nanointerconnects can be further reduced by laying a barrier layer. Compared with other materials, graphene is an ideal thin barrier layer material. Researchers have laid multilayer graphene on the four sides of Cu nanointerconnects, making it equivalent to a single conductor transmission line. First, they properly processed and analyzed the multilayer graphene, and found that as the thickness and mass of graphene grow, its inductance will increase, and its capacitance will remain unchanged. However, when graphene is laid on the Cu nanointerconnects, the resistance values measured by the Cu nanointerconnects are reduced, because graphene changes the grain size and mirror parameters of the Cu nanointerconnects. They then compared the time delay of Cu nanointerconnects with the transmission delay of Cu-graphene hybrid nanointerconnects, and found that graphene can reduce the transmission delay of nanointerconnects better than other traditional barrier layer materials [9]. And through further research, it was found that the thinner the thickness and the greater the mass of graphene, the smaller the transmission delay of the nanointerconnect. So next, when we analyze and simulate a Cu-graphene hybrid nanointerconnect in cst, we only consider the case of a monolayer graphene. The next chapter, we will simulate the properties of a Cu-graphene hybrid nanointerconnect and compare them with a bare Cu nanointerconnect.

## 3. Analysis of a Cu-Gra hybrid nanointerconnect

Currently, graphene is the thinnest two-dimensional material, it has a large mobility and a small mass. Graphene is linearly dispersed, and the Dirac cone is located at six corners of the hexagonal Brillouin region. Thus, the development of graphene interconnects has played a role in modeling and manufacturing. After that, people studied the parallel multilayer graphene nanointerconnect and vertical multilayer graphene nanointerconnect, the effect fell short of expectations, because as the number of layers of graphene increases, its properties will become more and more similar to

graphite, so it still could not meet the demand. Cu nanointerconnects are still a common choice for current technology [10].

However, as mentioned above, the characteristics of a Cu nanointerconnect will deteriorate with the extension of the length. Previously, some people studied the interconnection characteristics of graphene-carbon nanotube bundle nanointerconnect at different lengths, and compared them with the Cu nanointerconnect, we found that under the same manufacturing size, with the increase of the length of the interconnect, the delay ratio between the vertical heterojunction graphene-carbon nanotube bundle nanointerconnect and the Cu nanointerconnect will gradually decrease. At 32nm manufacturing size, the delay of the vertical heterojunction interconnect is larger than the Cu nanointerconnect, that is, the vertical heterojunction at 32 nm has no advantage in the delay of the interconnect. At 22nm, the delay of the vertical heterojunction interconnect is higher than that of the Cu nanointerconnect at the beginning, but with the increase of the length of the interconnect, the advantage of the vertical heterojunction interconnect delay is manifested, which is 70-79% of the Cu nanointerconnect delay. At 14nm, the advantages of vertical heterostructure delay are further demonstrated, which is only 38% to 47% of the delay of Cu nanointerconnect. At 32nm process size, the time delay of vertical heterojunction interconnects is always higher than that of horizontal heterojunction interconnects. At the process size of 22nm and 14nm, when the interconnect is shorter, the delay of the horizontal heterojunction interconnect will be smaller, but with the gradual increase of the interconnection length, the delay of the vertical heterojunction interconnect will be equal to or less than the horizontal heterojunction connection delay.

Now, due to the high resistance diffusion barrier will reduce the effective conduction area and deteriorate with the reduction of the size of the interconnect, more attention should be paid to the selection of the barrier layer of the Cu nanointerconnect, which is closely related to the performance of the chip. We mentioned that before, previous studies have investigated the electrical properties of graphene laid on a Cu nanointerconnect, which is a Cu-graphene hybrid nanointerconnect, and concluded that graphene can well reduce the propagation delay and temperature rise of traditional Cu nanointerconnects.

We know graphene can very well reduce the propagation delay and temperature increase of traditional Cu nanointerconnects. Previously, the properties of Cu-graphene hybrid nanointerconnects coated with graphene were studied by using the unconditionally stable finite-difference time-domain method through maxwell equations and Boltzmann transport equations. Here, we simplified the Boltzmann transport equation to extract a Drude model. Using this simplified model, we simulated it using impedance boundary conditions in cst. In order to compare the differences between different graphene models, we also selected two other Drude models extracted from other formulas for simulation comparison. We can analyze the difference in the performance improvement of graphene for a Cu nanointerconnect under the three different graphene Drude models.

In this chapter, the size of graphene is  $10nm \times 10um$ , and the relaxation time is  $\tau = 2 \times 10^{-11}s$ . Like the Cu nanointerconnect, we lay a monolayer graphene in both sides of the x direction, and only the top side of the z direction, and add current source in the z direction for simulation.

### 3.1 Drude-Lorentz Model of Graphene

In the beginning, the Drude-Lorentz model is used to study semiconductor optical plasmas, and when the loss is considered in the form of a complex dielectric function, we can obtain a theoretical solution for the propagation of electromagnetic waves along the semiconductor/dielectric interface at optical frequencies. By adding the loss term to the Drude model and Lorentz model, the numerical solution of the dispersion curve of semiconductor plasma can be obtained. Later, some people studied the physical properties of different metal materials such as gold, silver, and copper under the Drude-Lorentz model, and proposed methods to optimize them. Researchers also have studied the Drude - Lorentz model into the Maxwell equations, using the finite difference time domain method (fdtd) to analyze the metal-semiconductor-metal plasma waveguide and

microcavity resonator. Now, we use the Drude-Lorentz model to analyze the graphene model, which is also a Drude-like model [11].

First, we can simplify the graphene model. We all know that in the Thz band, since  $\hbar\omega \ll E_f$ , we can ignore the interband part of conductivity of graphene.

In the cst simulation, we can set a single layer of graphene with a very small thickness  $\Delta$ , we choose  $\Delta = 1nm$ . Drude-Lorentz model of graphene is a very important expression of dielectric materials. The expression for the permittivity of Drude-Lorentz model of graphene can be equivalent to equation (2).

$$\varepsilon_{eff}^{Gr}(\omega) = \varepsilon_0 + j \frac{\sigma_V^{intra}(\omega)}{\omega} = \varepsilon_0 + \frac{j\sigma_0^{Gr}}{\omega(1 - j\omega\tau)} \#(2)$$

We can analysis from the equation (2) that the real part of the dielectric constant gradually increases with frequency, while its imaginary part decreases with frequency.

After that, we introduce the dielectric constant into cst, we will create a new material, select the type as normal, choose the dielectric dispersion as user, and import the dielectric constant  $\varepsilon'$  and  $\varepsilon''$  calculated by MATLAB into it, then the new graphene material is obtained.

### 3.2 Drude Model extracted from Kubo Equation

We know that the Kubo formula is a method to obtain the dielectric constant, refractive index, plasma frequency of graphene by its conductivity. Due to its good properties, graphene is playing an increasingly important role in integrated circuits. It has been found that the phenomenon of Pauli blocking has a close relationship of the interband transition of graphene and it also has a directly relationship of the Fermi level of graphene, so we can change the dielectric constant of graphene by adjusting the Fermi energy of graphene. The conductivity of Kubo equation can extract the dielectric constants of graphene, so the accuracy of Kubo formula is very important. In article [12], the author discussed three different Kubo formulas and compares their dielectric constant, refractive index, electrical conductivity and so on. They concluded a most accurate formula which we will use later.

In microwave band, the conductivity of graphene is  $\sigma = \sigma' + i\sigma'' = \sigma_{intra} + \sigma_{inter}$ . We can describe the conductivity of graphene by two types of formulas, Kubo formula and Drude approximation formula. Kubo formula is suitable for microwave to visible light band, while Drude approximation formula is only suitable for microwave band [13]-[14]. By comparison, it can be concluded that there is no obvious difference in the conductivity between the two formulas, but the real part of the dielectric constant is different and the imaginary part is the same. After analysis, it is concluded that Drude formula lacks the part of interband transition compared with Kubo formula. On the other hand, Drude formula itself is too simplified. Therefore, when calculating the conductivity of graphene in the microwave band, both formulas can be used, and the Drude model itself is more conducive to calculation. So, in the following, we only consider the Drude model for graphene.

According to the Kubo formula, the conductivity of graphene can be divided into two parts, namely the intraband conductivity and the interband conductivity. In the terahertz range, the Kubo formula can only consider the conductivity in intra-band, the Drude model can be derived in equation (3)-(4).

$$\sigma_0 = \frac{e^2 k_B T}{\pi \hbar^2} \left[ \frac{\mu_c}{k_B T} + 2 \ln \left( 1 + e^{-\frac{\mu_c}{k_B T}} \right) \right] \#(3)$$

$$\sigma_s(\omega) = \frac{\sigma_0}{1 + j\omega\tau} \#(4)$$

In the cst simulation, the monolayer graphene is simulated using impedance boundary conditions. According to the microscopic quantum dynamics model, the impedance model of graphene can be obtained by  $Z_s$  [15].  $Z_s = R_s + iX_s$ ,  $R_s$  is the surface resistance related to energy dissipation caused by intra-band scattering of graphene, which is related to the real part of the Kubo formula,

$X_s$  refers to the surface reaction, which is related to the imaginary part of the Kubo formula. Then we take them to the impedance boundary conditions of cst to build a new graphene model. In this case, graphene is a two-dimensional plane. Detailed cst results are in chapter 3.4.

### 3.3 Drude Model extracted from Boltzmann Transport Equation

Due to the mean free path of graphene compared to the mean free path of Cu is very different, which can reach micron level, this will lead to that in the case of high frequency, graphene can lead to peculiar skin effect. The singularity of graphene skin effect and ohm's law is not compatible, at this time only the Boltzmann transport equation can solve the corresponding parameters of graphene.

In the semi-classical framework, the Boltzmann transport equation is the master equation for the distribution function, which expresses the probability that the electron states occupy the phase space. So, when we get the distribution function, the Boltzmann transport equation can get other unknowns. However, the Boltzmann transport equation is a complex six-dimensional phase space, so its analytical solution cannot be found directly, and the result needs to be obtained by programming. In the article [16], the author simplifies the six-dimensional phase space to the four-dimensional phase space for calculation, but the calculation is still very difficult.

However, a Drude model after simplifying Boltzmann transport equation is proposed in this paper. Three hypotheses are proposed, the real space of Boltzmann equation is removed, and the distribution function  $f_0$  is unified as Fermi-Dirac distribution function, the differential equation in time domain is converted to the form in frequency domain. A general Drude model is obtained by the current density formula of graphene. In the article [17], by comparing the current density of graphene obtained from the original Boltzmann transport equation with the simplified Drude model, it is found that the curves obtained from the analytical and numerical solutions of the Drude model are consistent with those obtained from the Boltzmann transport equation in the time domain. Therefore, in the following we will only consider the Drude model of graphene.

It is known that the Boltzmann equation can control the charge carrier distribution function of graphene  $f(r, k, t)$ . The Boltzmann transmission equation is as follows [18]:

$$V \cdot \nabla_r f + \frac{q}{\hbar} E \cdot \nabla_k f + \frac{\partial f}{\partial t} = - \frac{f - f_0}{\tau} \#(5)$$

Let's make three assumptions:  $f(r, k, t)$  is very small, so that  $v \cdot \nabla_r f \approx 0$ . The outfield is very small, which is causing little change in the Fermi Sea. So in  $k$  space,  $f \sim f_0$ ,  $\frac{q}{\hbar} E \cdot \nabla_r f \sim \frac{q}{\hbar} E \cdot \nabla_r f_0$ . We can ignore the nonlinear effects, so we can analyze  $\frac{\partial f}{\partial t}$  in the frequency domain using  $j\omega \tilde{f}$ .

We can obtain the charge carrier distribution  $\tilde{f}$  by the assumptions, graphene conduction current density can be calculated by integrating over  $k$  space, where  $g_s = 1$ ,  $g_v = 2$ .  $d$  is valued according to the dimension, taking the values of 2 and 3 under 2D and 3D, respectively.

We exploit the symmetry of the linear dispersion and the symmetry of the Fermi sphere to simplify the integral. Since  $f_0$  is even and  $v$  is odd in  $k$  space, the integral of  $f_0 v$  is 0.  $\int_k (-\nabla_k f_0) \hat{k} dk$  is isotropic due to its symmetry, so we can write it as an identity matrix. So, we can get the formula (6)-(7).

$$\tilde{j}_g = \frac{\tilde{E}}{1 + j\omega\tau} \cdot \frac{\tau q g_s g_v q}{\hbar (2\pi)^d} v_F \int_k (-\nabla_k f_0) \hat{k} dk = \frac{\sigma_0 \tilde{E}}{1 + j\omega\tau} \#(6)$$

$$\sigma_0 I = \frac{\tau q g_s g_v q}{\hbar (2\pi)^d} v_F \int_k (-\nabla_k f_0) \hat{k} dk \#(7)$$

We can obtain the Drude model of graphene conductivity by above equations.

$$\tilde{\sigma}_g(\omega) = \frac{\sigma_0}{1 + j\omega\tau} \#(8)$$

Like chapter 3.2, graphene is simulated with impedance boundary condition in cst. Detailed cst operations are following: first, we also set the size to  $um$  and establish a cube model of  $10nm \times 10nm \times 10um$ . The difference is, we create a new material which is used as graphene. The graphene is setted as impedance boundary condition, we set material frequency as  $25Ghz$ . According to the formula calculation above,  $Rs$  is equal to  $2\Omega/sq$  and  $Xs$  is equal to  $6\Omega/sq$  for Cu-gra and Kubo-Drude model,  $Rs$  is equal to  $2\Omega/sq$  and  $Xs$  is equal to  $0.4\Omega/sq$  for Cu-gra and Boltzmann-Drude model. The graphene is set as a two-dimensional plane, we also assume that the Cu nanointerconnect extends along the y direction, we lay a monolayer graphene in both sides of the x direction, and only the top side of the z direction, respectively. The rest of the operations is the same as the Cu nanointerconnect. Simulation is carried out and the detailed results of the simulation are shown in the next chapter 3.4.

### 3.4 Cst Simulation Results

We use cst to simulate, the voltage and propagation delay of a Cu-graphene hybrid nanointerconnect over time.

The results shows that the maximum voltage of the Cu-graphene hybrid nanointerconnect varies with the Drude model for different graphene. The details are summarized in Table 1. The results also shows that the time transmission delay of the Cu-graphene hybrid nanointerconnect is improved which is compared with the Cu nanointerconnect, although the change is very small. The detailed comparing by Cu nanointerconnect is summarized in Table 2.

The results of the Cu nanointerconnect and the Cu-graphene hybrid nanointerconnect are compared in the following Table 1. and Table 2.

Table 1. maximum voltage comparing

Feature Size	bare Cu	Cu-gra, Drude-Lorentz	Cu-gra, Kubo-Drude	Cu-gra, Boltzmann-Drude
10nm×10nm×10um	42nV	39nV	36nV	31nV

Table 2. port propagation delay comparing

Feature Size	bare Cu	Cu-gra, Drude-Lorentz	Cu-gra, Kubo-Drude	Cu-gra, Boltzmann-Drude
10nm×10nm×10um	2.251ps	2.038ps	1.804ps	1.583ps

From the above two tables, we can see that the voltage of the Cu nanointerconnect coated with graphene is significantly reduced, and the propagation delay is also reduced. The simulation results show that when the thickness of graphene is very thin, the effective conduction area of the nanointerconnect is almost not affected, and the resistivity of the nanointerconnect will not increase but decrease. For these three Drude models, the most important difference is  $\sigma_0$ , because the conductivity of graphene determines the dielectric constant, refractive index and plasma frequency of graphene. So, although different graphene Drude models can reduce the voltage of Cu nanointerconnect and reduce its transmission propagation delay. However, the Drude models extracted by different formulas are still very different in essence, so their voltage reduction effects and transmission propagation delay reduction are also very different. At the same time, the Drude model derived from Boltzmann equation can minimize the voltage of Cu nanointerconnect and reduce the transmission delay of the two ports of the nanointerconnect.

## 4. Summary

From the above analysis, we can see that the Cu-graphene hybrid nanointerconnect can effectively reduce the resistivity, improve the conductivity, and reduce the voltage. And the propagation delay of the Cu nanointerconnect with graphene as the protective layer is effectively

optimized. So, we can see that Cu-graphene hybrid nanointerconnects with different Drude models can contribute to the development of integrated circuits (IC).

In this paper, we discussed the relevant characteristics of Cu-graphene hybrid nanointerconnects under different graphene Drude models under cst simulation. If there are new graphene models, we can still discuss them according to the above methods to obtain corresponding results. However, because it is the result of simulation, there may still be a certain deviation from the actual Cu-graphene hybrid nanointerconnect, which needs to be solved, and it is essential to fabricate an ultra-thin barrier layer with low resistivity around the Cu nanointerconnect. Until now, depositing ultra-thin barrier layers has remained a key challenge. At present, the relevant materials and technologies for manufacturing barrier layers less than 2 nanometers thick remain challenging. This is a problem we have to overcome in the future. Once these problems are solved, the development of integrated circuits will go further.

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