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A susceptor heating structure in MOVPE reactor by induction heating

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HIGHLIGHTS

- A novel susceptor with V-shaped slot in MOVPE reactor is proposed.
- Temperature in the substrate is optimized.
- Great temperature uniformity of the substrate is obtained.

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ABSTRACT

A novel susceptor with a revolutionary V-shaped slot of solid of revolution form is proposed in the metalorganic vapor phase epitaxy (MOVPE) reactor by induction heating. This slot changes the heat transfer rate as the generated heat is transferred from the high temperature region of the susceptor to the substrate, which improves the uniformity of the substrate temperature distribution. By using finite element method (FEM), the susceptor with this structure for heating the substrate of six inches in diameter is optimized. It is observed that this optimized susceptor with the V-shaped slot makes the uniformity of the substrate temperature distribution improve more than 80%, which can be beneficial to the film growth.

1. Introduction

Thin films of GaN-related material are widely used in optoelectronic devices such as laser diodes and optical modulators [1,2]. Metalorganic vapor phase epitaxy (MOVPE) is a widely used technology to grow thin epitaxial layers of various semi-conducting materials [3]. In the MOVPE reactor, the uniformity of the temperature distribution in the substrate has a great influence on the film growth [4]. However, due to the skin effect of the induced current in the conventional MOVPE reactor by induction heating, the temperature distribution in the substrate is non-uniform [5].

By now, many studies have been done about this question. M.H. Tavakoli et al. [6]studied the effects of the section shape and location of the coils on the temperature distribution. H. Hanawa et al. [7] proposed a multi-zone heating structure heated by induction, and its main method is that each heating zone is separately powered, aimed at improving the uniformity of the substrate temperature distribution. A.I. Gurary et al. [8] studied a heating structure with a flat coil in the CVD reactor heated by induction, and they pointed out this structure weakens the effect of the magnetic force produced on the upper surface of the susceptor on the substrate carrier. Huang et al. [9] have investigated the influences of the single-layer coils and the multilayer coils on the temperature, and they found that the structure of the multilayer coil can improve the temperature uniformity.

Li et al. [10] found that the temperature distribution in the substrate with the coils under the graphite susceptor is more uniform than that with the coils around the outside wall of the reactor, and the standard deviation of the temperature distribution in the six-inch substrate is reduced to 9 °C. In our previous study, we put forward a susceptor with a ring slot to optimize the temperature distribution of the substrate and got a good result [11], but this slot is not suitable to be used to optimize the larger susceptor, especially the susceptor with the diameter of more than 5 inches. It can be

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seen that the uniformity of the substrate temperature distribution is still a question needed to be solved. According to the study of the temperature in the susceptor, it is found that in the conventional susceptor the higher temperature region is located around the bottom of the susceptor and is distributed as a ball, which can be seen in Fig. 2(b) of the Ref. [10], So in this work, a V-shaped slot is proposed, aimed at weakening the rate of the heating transfer of the heat source from the center of the heat source to the substrate, and improving the uniformity of the temperature distribution in the substrate.

2. Model and structure of MOVPE reactor

In this paper, the magnetic potential vector theory is used to calculate the magnetic field and the Joule heat. The detailed magnetic vector potential equation derived from the Maxwell's equations and boundary conditions are referred from (1) to (4) of Ref. [12]. In addition, a heat conduction equation with the convective term is used to obtain the temperature distribution in the MOVPE reactor [13]:

$$c_j\rho_j\left(\frac{\partial TT}{\partial t}+\vec{V}\nabla T\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(k_j r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k_j\frac{\partial T}{\partial z}\right)+Q_{\mathrm{eddy}} \tag{1}$$

where c_j is the specific heat, T is the temperature, $\vec{V}$ is the fluid velocity vector, ρ_n is the density and k_j is the thermal conductivity of the material j (Because five major materials are used in the simulation such as the graphite susceptor, SiC substrate, the alumina ceramic strut, the quartz tube and the hydrogen in the reactor, $j = 5$.). t is time and Q_{eddy} is the heat source term due to eddy currents that can be calculated as:

$$Q_{\mathrm{eddy}} = \frac{1}{2}\sigma\omega^2 A_0^* A_0 \tag{2}$$

where ω and σ are angular frequency and the electrical conductivity, respectively, A_0 is the magnetic potential vector, and A_0^* is the complex conjugate of A_0.

Fig. 1(a) shows the simulation model of the MOVPE reactor with the conventional susceptor. The following parts are included: the upper and lower flanges, the alumina ceramic strut, the graphite susceptor, coils, the quartz tubes, the SiC substrate and so on, which are axisymmetric in 2D. Therefore, a two-dimensional axisymmetric FEM model is used in the simulation and the symmetric boundary condition of the heat is:

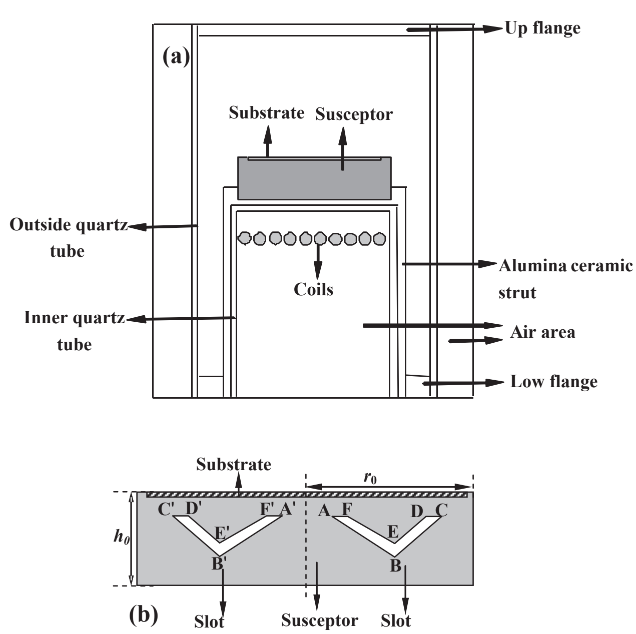

Fig. 1. Simulation model of MOVPE reactor (with conventional susceptor) (a) and susceptor with V-shaped slot (b).

$$\frac{\partial T}{\partial r} = 0 \quad \text{at} \quad r = 0 \tag{3}$$

Fig. 1(b) shows the axis-sectional schematic diagram of the novel susceptor structure mentioned in this paper. h_0 is the height of the susceptor. r_0 is the radius of the susceptor. In this susceptor, a V-shaped slot of solid of revolution form is used in the conventional susceptor, in which there are six vertices in the slot, and their coordinates are as follows: A(x_a,y_a), B(x_b,y_b), C(x_c,y_c), D(x_d,y_d), E(x_e,y_e), F(x_f,y_f).

The slot is used to change the single heat transfer mode in the conventional susceptor. Thus, one part of the heat generated in this susceptor is transferred to the center and edge of the substrate by heat conduction along the sides BA and BC as well as B′A′ and B′C′ of the slot shown in Fig. 1(b), and the others to the substrate area on the upper slot mainly by heat radiation. So the uniformity of the temperature distribution in the substrate can be improved by optimizing the size and location of the slot.

During the film growth, the hydrogen (H_2) is usually used as the carrier gas, and in most MOVPE for the growth of nitride film, H_2 occupies most of the gas and the percentage of H_2 is more than 90% [4,14,15], thus the gas used in the simulation is pure H_2. Meanwhile, because of the relatively short path in MOVPE reactors, the gas is assumed transparent to the infrared emission. At the inner walls of the reactor, the outer surfaces of the susceptor and substrate and the other walls, the radiation and convection boundary condition is

$$-k_i\frac{\partial T}{\partial \vec{n}} = h_i(T-T_i)+\sigma_{\mathrm{SB}}\varepsilon_i\left(T^4-T_i^4\right), \tag{4}$$

where k_i is the thermal conductivity and h_i the Newtonian heat transfer coefficient (which is set to be 7.5 W/m^2 K [16]) of the *i-th* material, $\vec{n}$ the unit normal vector, ε_i the emissivity of the *i-th* material, T_i is the temperature of the surface of the *i-th* material and σ_{SB} the Stefan–Boltzmann constant (5.67 × 10^{-8} W/m^2/K^4). The Equation (4)denotes the transfer via radiation and convention from the surfaces.

Due to the water-cooled quartz tube during the film growth, the temperature of the surfaces of the quartz tube walls is kept at 25 °C, and the initial condition of temperature in the system is set to be 25 °C.

In this work, A finite element code with Galerkin's formulation is used to predict the power densities and temperature distribution in the reactor, and the coupled electro-magneto-thermal analysis is shown in Fig. 3 [17]. The flow chart of the numerical scheme of computation coupled with electro-magnetic-thermal analysis is shown in Fig. 3. In addition, the hidden method is used to calculate view-factors in order to calculate radiative heat transfer rates, and the detailed steps are referred to the Use's Manual of Release 10.0 of ANSYS. All the material data used are referred to the Appendix. After the model being meshed freely, taking the skin effect into account, a remeshing method is employed near the bottom of the susceptor and the independence of the solution with respect to the mesh size is checked by examining the maximum surface temperature. The 2D axi-symmetric electro-magnetic and thermal domain with the main boundaries is shown in Fig. 2(a), and the 2D mesh plot of the reactor and the detailed mesh of the susceptor with the substrate are shown in Fig. 2(b). The time increment of the iteration time is 40 s. A default value of 10^{-6} for convergence on heat flow is used.