

A REVIEW ON STEALTH PRINCIPLES

DONGQING PANG¹ & YICAI SUN²

¹Ultrafast Laser Laboratory, Key Laboratory of Opto-electronic Information Technology (Ministry of Education),
College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin, China

²Hebei University of Technology, Tianjin, China

ABSTRACT

The principles about the reflection and absorption of electromagnetic wave propagation in solids are introduced to such as radar and infrared light stealth technology, so the stealth effect of light trapping mechanism is illuminated. Stealth materials are always composed of multiply films. The surface films are transparent ones with lower reflectivity to electromagnetic wave propagating in solids and the bottom films are high absorption ones either for radar or for infrared light. It is also described how to select surface films and bottom films, focusing on the relations to their dielectric constants, porosity (cavity), densities of free carries and vibrators, the species as well as the width of forbidden gap of semiconductors in order to get the best stealth effects so as to disclose stealth aircrafts. In addition, the applications of light trapping films and photon crystals in stealth technologies are briefly introduced.

KEYWORDS: Stealth Principles, Electromagnetic Wave, Infrared Light, Reflectance, Absorption, Light Trapping Mechanism, Stealth Aircrafts

1. INTRODUCTION

Stealth technology plays a very important role in the aircraft, battle tanks, warships, rockets, missiles; it is an important part of national defense technology¹. Weapon system using stealth technology can reduce the detection rate; promote its own survival, increases aggressiveness so as to get the most direct military benefits.

As far as weapons and equipment on the ground, stealth technology is mainly used to prevent the radar or infrared device detection, radar guidance weapons and laser guided bomb attacks; It is said for combat aircraft, stealth technology is used to prevent detection by the AWACS radar, fire control radar and infrared device in airplanes, to prevent attacks by active and semi-active radar and air-to-air missiles and infrared fighting missile¹. Study on stealth films is an important part of stealth technology in the premise of equipment shape unable to be changed. Stealth film materials are bases to realize anti- detecting stealth technology.

Through the introduction of reflection and absorption rules for electromagnetic wave propagation in solids, this paper would like to clarify the basic principle of the anti- detecting stealth technology, and introduces the design and performance of stealth materials in anti- detecting technology.

According to the frequency from low to high, electromagnetic wave are followed by radio waves, radar, and microwave, infrared, visible light, ultraviolet rays, X rays and gamma rays. However, anti - detecting stealth technology materials mainly include two kinds of radar and infrared absorbing stealth materials.

1.1 Radar Wave-Absorbing Materials^{1]}

1.1.1 Structural Radar Absorbing Materials used in Anti-Sensing Stealth Technology

These are a kind of multifunctional composite materials with a high stealth performance, such as good dielectric transmission quartz fiber, polyethylene fiber, PTFE fiber, ceramic fiber, glass fiber, polyamide fiber, aramid fiber and carbon fiber, polyurethane foam, light and magnetic loss filler, being able to better absorb or transparent through electromagnetic wave. These kinds of wave absorbing materials are used in A-12, F-111 aircrafts, B-1B and harrier II aircrafts and Japanese air to warship missile ASM-1 and land to warship missile SSM-1 as warship bombs;

1.1.2 Radar Absorbing Coatings in Stealth Technology

Including the magnetic loss and power loss coating paint composed by magnetic filler such as the ferrite dispersed in dielectric polymers, this coating has good absorption in the low frequency band, with high stealth performances.

1.2 Infrared Stealthy Materials^{1]}

Infrared stealthy materials are the most important thermal infrared stealth materials in their varieties, those stealth materials have been also developed in recent years, being compatible with infrared, millimeter wave and visible light.

1.2.1 Tin Doped Indium Oxide Expensive Wave-Absorbing Materials

Being compatible with infrared, millimeter wave and visible light;

1.2.2 The Metal Short Fiber, Barium Titan ate Ceramic, Graphite Powder and ZnO Cheap Wave-Absorbing Materials

2 . THE STEALTH PRINCIPLE-INTERACTION OF ELECTROMAGNETIC WAVE WITH STEALTHY MATERIALS

2.1 Electromagnetic Wave Propagation^{2]}

The amplitude A of electromagnetic wave Ψ for propagation with an angular frequency ω in solids could be expressed as the following:

$$\Psi = A \exp\{\omega i(t - x/c')\} \quad (1)$$

Where c' is the velocity of light in solids: $c'/c = n - ik$, c is the velocity of light in air and $\eta = n - ik$ is the complex refractive index of solids. n is the refractive index. Introducing c' into expression (1), there is $\Psi = A \exp\{\omega i(t - (n - ik)x/c)\} = A \exp(\omega ikx/c) \exp\{\omega i(t - nx/c)\}$. The strength I of electromagnetic wave is $I = \Psi\Psi^* = A^2 \exp(-2\omega kx/c) \exp\{\omega i(t - nx/c)\}$. Its intensity attenuation along x is $dI/dx = -I_0/\alpha$, I_0 is the intensity before accessing into solids then

$$I = I_0 \exp(-\alpha x), \text{ thus } \alpha = 2\omega k/c = 4\pi k/\lambda \quad (2)$$

Where α and k are respectively called absorption coefficient and absorption index; electromagnetic wave length;

2.2 The Motion Equation of Electrons in Samples under the Action of Electromagnetic Wave Irradiation^{3, 4]}

Free electrons in the sample will cause the response under the effects of electromagnetic field in incident radiation.

If angular frequency of the applied the electromagnetic field is ω , so free electrons move as sinusoidal variation with this angular frequency ω :

$$m^* \frac{d^2x}{dt^2} + m^* \nu \frac{dx}{dt} = qEe^{i\omega t} \tag{3}$$

And the displacement of relative coordinate x:

$$x = -\frac{qE}{m^*(\omega^2 - i\omega\nu)} \tag{4}$$

Where q- electronic charge; E-the strength of electric field of the electromagnetic field; m*-free electron effective mass; ω angular frequency of electromagnetic field; ν -the collision frequency of electrons to lattice. Polarization strength due to free electrons is:

$$P_e = Nqx = -\frac{Nq^2E}{m^*(\omega^2 - i\omega\nu)} \tag{5}$$

Polarization strength P_e -arisen from free electrons free electron numbers in unit volume (1/cm³); Complex permittivity of materials is: $\tilde{\epsilon} = \epsilon_r + P_e / \epsilon_0 E$

Where $\tilde{\epsilon}$ -complex dielectric constant of materials; ϵ_r relative dielectric constant of materials; ϵ_0 -vacuum dielectric constant.

Table 1: Relative Dielectric Constant ϵ_r of Some Materials⁵¹

crystals	ZnO	GaAs	InSb	Si	TeO2	LiTaO3
ϵ_r or ($\epsilon_{11} / \epsilon_{33}$)	9.16/12.6	12.5	16.8	11.8	22.9/24.7	51/45
crystals	SiO2	LiNbO3	Ge	PZT-5A	Bi ₁₂ GeO ₃₀	SnO2
ϵ_r or ($\epsilon_{11} / \epsilon_{33}$)	4.52/4.68	84/30	16	1730/1700	40	n=2

Thus, obtaining: $\tilde{\epsilon} = \epsilon_r \left[1 - \frac{Nq^2}{m^* \epsilon \omega(\omega - i\nu)} \right]$ (7)

Where $\epsilon = \epsilon_0 \epsilon_r$ -dielectric constant of materials. We define ω_p as plasma resonance frequency:

$$\omega_p^2 = \frac{Nq^2}{m^* \epsilon} \tag{8}$$

So there is: $\tilde{\epsilon} = \epsilon_r \left[1 - \frac{\omega_p^2}{\omega(\omega - i\nu)} \right]$ (9)

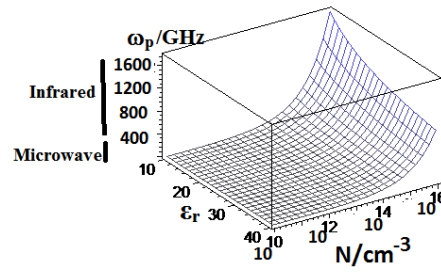


Figure 1: Relationship among ω_p and ϵ_r Free Electron Concentration

$$\text{Then } \tilde{\epsilon} = \epsilon_r \left[1 - \frac{\omega_p^2}{\omega(\omega - i\nu)} \right] = \epsilon_r \left[1 - \frac{\omega_p^2(\omega + i\nu)}{\omega(\omega^2 + \nu^2)} \right] = \epsilon_r \left(1 - \frac{\omega_p^2}{\omega^2 + \nu^2} \right) - i \frac{\omega_p^2 \nu \epsilon_r}{\omega(\omega^2 + \nu^2)} \quad (10)$$

Known by electromagnetic field theory, complex dielectric constant $\tilde{\epsilon}$ is equal to square of the complex refractive index of $n - ik$ ^{2, 3)} in semiconductors, i.e.:

$$\tilde{\epsilon} = \eta^2 = (n - ik)^2 \quad (11)$$

$$\text{When } k \approx 0, \tilde{\epsilon} = (n - ik)^2 = (n^2 - k^2) - 2nki \approx n^2 \text{ there for } n = \sqrt{\tilde{\epsilon}} = \sqrt{\epsilon_r \left(1 - \frac{\omega_p^2}{\omega^2 + \nu^2} \right)}$$

Because of $\nu \ll \omega$, ν can be neglected, thus:

$$n = \sqrt{\epsilon_r \left(1 - \frac{\omega_p^2}{\omega^2} \right)} \quad (12)$$

It can be seen from expression (12) that when $\omega_p > \omega$, $\tilde{\epsilon}$ is negative, this explains the propagation of electromagnetic wave does not occur in solids with a total reflection. Only when $\omega > \omega_p$, it is positive, i.e. the electromagnetic wave can transmit through solids without total reflection.

Reflection of the incident electromagnetic wave from solids^{3, 4)}

$$\text{Reflection } R \text{ for the incident electromagnetic wave is } R = \frac{[(n-1)^2 + k^2]}{[(n+1)^2 + k^2]} \quad (13)$$

$$\text{When the absorption index } k \text{ is close to zero, there are: } R = \left(\frac{n-1}{n+1} \right)^2 \quad (14)$$

In addition, according to expression (13), when $k \approx 0$, we can deduce the relationship between R and ω of the incident electromagnetic wave:

$$R = \left(\frac{\sqrt{\epsilon_r \left(1 - \frac{\omega_p^2}{\omega^2}\right) - 1}}{\sqrt{\epsilon_r \left(1 - \frac{\omega_p^2}{\omega^2}\right) + 1}} \right)^2 \tag{15}$$

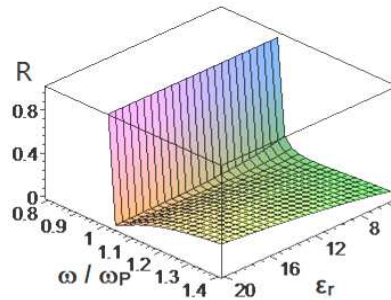


Figure 2: Relationship among R, ω / ω_p and Relative Dielectric Constant ϵ_r

Figure 2 shows the relationship among R, ω / ω_p and ϵ_r . It can be seen from Figure 2 that when ω / ω_p large, R is close to 30~40% in the ideal semiconductor case. When ω / ω_p decreased, R decreases. When ω / ω_p is slightly greater than 1, R decreased to 0, i.e. the emergence of a minima. When $\omega / \omega_p = 1$, R rapidly increase to 100%. Therefore, in short wave cases, R is close to 30~40%, while R is very high in the long wavelength cases.

The stealth purpose is how to improve high reflectivity and low emission ratio for the used materials. Through modulating doping process to reduce the carrier concentration up to $10^{14}/\text{cm}^{-3}$ (see Figure 1) and use of a temperature control technology to reduce ω_p , let the lightly doped semiconductor coating and absolute materials possess with low reflectivity in the thermal infrared or microwave bands (i.e. the band with close to or greater than ω_p) so as to achieve the stealth effect.

It can be visible from expression (8) that ω_p is relevant to N concentration of free carrier in samples, the smaller the N, then the smaller is the ω_p , as we know that total reflection frequency happened at so that total reflection frequency is shifted to lower frequency, that is to say, non- total reflection frequency is extended, so the better is stealth effect.

In addition, from expression (15) it can be seen that only when ω_p is lower, then ω/ω_p will be larger, away from the total reflection frequency for microwave.

At this time, R reflectivity of materials is related to dielectric constant ϵ_r , the smaller ϵ_r , then the smaller is the reflectivity R. Novel thermoplastic PEEK, PES, PPS and epoxy resin, thermosetting bismaleimide, polyimide, polyether imide and isocyanate possess a relative small relative dielectric constant ϵ_r , thus those composite materials has good radar transmission properties. The varied fibers comprises of quartz fibers, polyethylene fibers, PTFE fibers, ceramic fibers, glass fibers, polyamide fibers and carbon fibers. It is of special significance as wave-absorbing structure.

There are two main ways to reduce dielectric constant ϵ_r of materials at present solid technology: reducing polarization and material density. The method of reducing the polarization is introduction of elements with small atomic

radius; Method for reducing the density of the material is introduction of macromolecule organic matter (aromatic polyimide, fluoride etc.) and the introduction of a vacancy (holes, voids). So these kinds of low ϵ_r medium are: doped and porous silica, organic polymers, such as fluorine doped silica (SiOF) with $\epsilon_r = 3$. Figure 3 shows the structure of some of the low ϵ_r materials^{6]}.

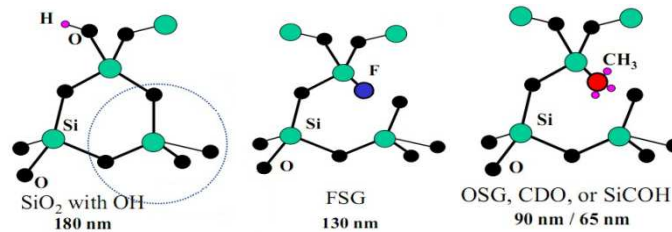


Figure 3: The Structure of Low ϵ_r Materials

Introducing micro porosity into the low ϵ_r medium is equivalent to reduce average dielectric constant within air and the low ϵ_r medium. Addition of carbon element to silicon matrix to reduce the dielectric constant is a good widely used method at present semiconductor technology with the formation of much porous structure in the stealth membrane. Table2 lists the current study in low ϵ_r dielectric material and dielectric constant at present semiconductor technology. Thus, porous SiO₂、perlite and polypropylene powder are the best choice as stealth materials.

Table 2: Low ϵ_r Dielectric Materials and their Dielectric Constant

Classification for Materials	Materials	Relative Dielectric Constant
SiO ₂	SiO ₂	4.0
C-Doped SiO ₂	SiOC	2.3-2.7
F-Doped SiO ₂	SiOF	3.4-3.7
Porous SiO ₂	Porous SiO ₂	1.1-2.5
Organic polyimide	Polyimide and polynaht-halene series	1.8-3.5
Organic polyimide	BCB(benzocyclobyt-ene)	2.7
Organic polyimide	Aromatic hydrocarbon (SiLK)	2.6
Organic compound	POLYPROPYLENE	1.5
Organic compound	POLYPROPYLENE POWDER	1.25
Organic compound	POLYETHYLENE	2.2-2.4
Organic compound	POLYBUTYLENE	2.2-2.3
Organic compound	POLYCAPROLACTAM	2.0-2.5
Mineral	PERLITE	1.3 - 1.4

2.4. The Effect of Porosity in Stealth Materials on Reflectivity^{7]}

The above discussed reflectivity principle is suitable for the sample with a smooth surface. When the sample with rough surface or pressed by powder, we should consider the effect of surface porosity h on refractive index n , due to diffuse reflection. The following formula was reported by literature^{7]}:

$$n_h^2 = (n_0^2 - 1)(1 - h) + 1 \quad (16)$$

Where h —surface porosity;

n_h —refractive index for a rough surface with porosity h ;

n_0 —refractive index for a smooth surface of a sample;

$$n_0 = n = \sqrt{\epsilon_r \left(1 - \frac{\omega_p^2}{\omega^2}\right)} = \sqrt{\epsilon_r \left(1 - \frac{\lambda^2}{\lambda_p^2}\right)} \tag{17}$$

After introducing it into expression (14), there is:

$$R_h = \left(\frac{\sqrt{\left[\epsilon_r \left(1 - \frac{\lambda^2}{\lambda_p^2}\right) - 1 \right] (1-h) + 1 - 1}}{\sqrt{\left[\epsilon_r \left(1 - \frac{\lambda^2}{\lambda_p^2}\right) - 1 \right] (1-h) + 1 + 1}} \right)^2 \tag{18}$$

Taking silicon as an example, and introducing ϵ_r and h as variable parameters into expression (18) for plotting R- h diagram, it can be seen that porosity h affects on the infrared reflection spectrum as shown in Figure 4. Though porosity h affects not only the values of reflectance, but also affects the position λ_0 (a litter longer than λ_p)at minimum values of reflectivity in infrared spectrum with increase of porosity h , λ_0 moving towards a long wavelength, benefit for broadening the wavelength range for stealth, that lays the theoretical foundation for the development of stealth sandwich materials. Sandwich materials generally consist of a surface film and a core component, the surface film is a wave transparent material, sandwich is a honeycomb structure with electromagnetic loss materials and infrared stealthy materials as the large porosity core.

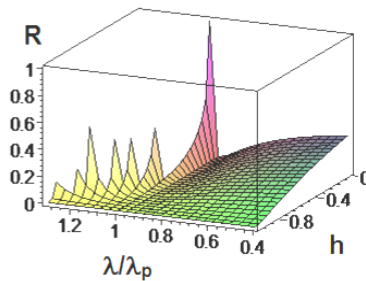


Figure 4: Porosity Affects on the Infrared Reflection Spectrum with Silicon

Thus, the reflection to electromagnetic waves or infrared light is very small, so most of them are absorbed into inner films. For example, when the radar wave irradiates over fuselage and wings of B-2 plane, first of all, wave induces transparently through the multilayer skin into the honeycomb core and as to be absorbed, the density of this absorbing stealth honeycomb core material is 0.032g/cm^3 with an attenuation up to 20dB at $6\sim 18\text{GHz}$ ¹¹. Figure5 shows the experimental results in infra-red reflective spectrum of silicon on different surface rough conditions with porosity.

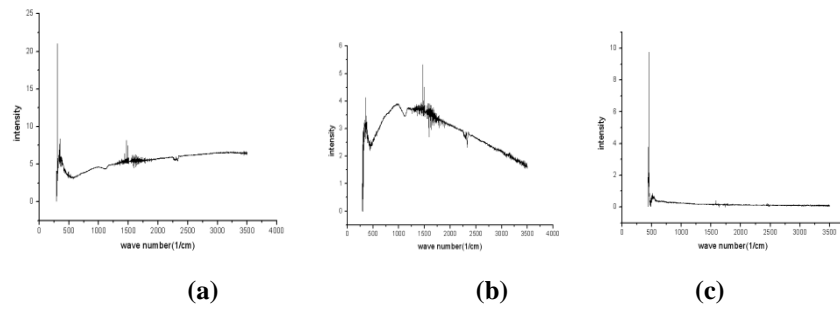


Figure 5: The Infra-Red Reflective Spectrum of the Polishing (a), Grounding(b), Pressed Powder Silicon with the Same Doping Density

It can be seen from Figure 5 that the surface roughness reduces reflectance and does basically not change the wave number positions (about 500 cm^{-1} , i.e. $\lambda_0 \sim 20 \mu\text{m}$) of minimum reflectance as $N = 6.35 \times 10^{18} \text{ cm}^{-3}$

2.5 Electromagnetic Wave Absorption Coefficient in Stealth Materials

2.5.1 Infrared Light or Micro Wave Selection Rule for Electric Dipole Oscillators^{8, 91}

When samples were irradiated with infrared light, the electromagnetic field energy can be absorbed only relying on the interactions between dipole moments and the electric field. According to the radiative transition on the theory of quantum mechanics, the absorption of electromagnetic radiation photon energy $h\nu = h\omega/2\pi$ is proportional to the probability W by the transition from the vibration ground state to the excited state as the following formula^{8, 91}:

$$W = \frac{8\pi^3}{3h^2} \left| \vec{\mu}_{p0} \right|^2 \rho(\nu_{p0}) \quad (19)$$

Where h —Planck constant $\rho(\nu_{p0})$ — electromagnetic wave energy density; $\left| \vec{\mu}_{p0} \right|$ dipole transition matrix element from the initial state O to the P state of the oscillator. The intrinsic dipole moment μ of the oscillator in crystals can be expanded into a series by using normal vibrational coordinates Q_k :

$$\mu = \mu_e + \sum_K \left(\frac{\partial \mu}{\partial Q_K} \right) Q_K + \frac{1}{2} \sum_K \sum_e \left(\frac{\partial^2 \mu}{\partial Q_K \partial Q_l} \right) Q_K Q_l, \quad l=1, 2, 3, \dots \quad (20)$$

Where μ_e — dipole moment value in the balance position ; Q_K, Q_l — normal vibrational coordinates

$$K, l=1, 2, 3, \dots \quad (21)$$

If a kind of normal vibration mode causes the first order of electric dipole moments (the second item in expression 20), then this vibrational mode would be infrared active, but the frequency of infrared wave depends upon its symmetry. Those belong to the same modes of vibration have the same frequency, and show the same behavior to cause changes of the dipole moment¹⁰¹. This is the selection rule of symmetry for infrared absorption. That is to say, the frequency of infrared wave is related with vibration modes so as to absorb infrared wave energy¹⁰¹. So far as stealth materials, the more categories of vibration modes, the more rich of infrared wave frequency or wavelength. The more is extended wavelength range of infrared wave with invisible and undetected properties.

2.5.2 Electromagnetic Field Intensity Attenuation

When electromagnetic wave propagation in stealth materials, the electromagnetic field intensity attenuation will occur with distance in sample depth, which is directly related to the absorption coefficient of the materials. There are already formulas (2) about its absorption coefficient and absorption index k . That is to say, the attenuation degree of the electromagnetic wave intensity I with distance at depth of sample is closely concerned with the absorption index k in the imaginary part of the complex refractive index $\eta = n - ik$.

2.5.3 The Motion Equation of Vibrators in Samples under the Action of Electromagnetic Wave Irradiation²¹

This vibrator composts of an atom with a restrain electron as a negative ion and a positive atomic core as a positive ion. The motion equation of vibrator under the action of electromagnetic wave irradiation is the following:

$$m_e \frac{d^2x}{dt^2} + m\nu \frac{dx}{dt} + Kx = qEe^{i\omega t} \tag{22}$$

Where $K = m_e \omega_0^2$ and $\omega_0 = \sqrt{K/m_e}$ being called natural or intrinsic angular frequency. The solution of this equation for displace x of the vibrator is:

$$x = \frac{qEe^{i\omega t}}{m_e(\omega^2 - \omega_0^2 - i\nu\omega)} \tag{23}$$

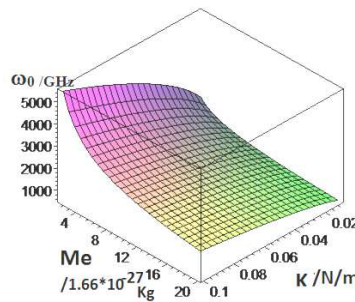


Figure 6: Relationship of ω_0 among m_e and K

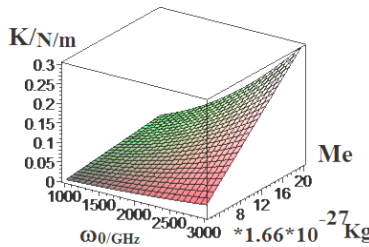


Figure 7: The Relationship of K among ω_0 and m_e .

Where m_e is effective mass of the vibrator, for example $m_e = m_1 m_2 / (m_1 + m_2) = 10.2 \times 1.66 \times 10^{-27} \text{ Kg}$ for the vibrator such as Si-O bond, K is force constant and ω_0 is the intrinsic frequency of the vibrator, $m\nu dx/dt$ is the damping force to lattice with a colliding frequency ν . Figure 6 shows the relationship of the intrinsic frequency among

effective mass and force constant. Figure 7 shows the relationship⁷¹ of the force constant K and intrinsic frequency ω_0 as the effective mass m_e near $10.2 \times 1.66 \times 10^{-27} \text{ Kg}$ of Si-O bond. The intrinsic frequency ω_0 of Q3 vibration mode for Si-O bond is 1136 cm^{-1} i.e. $\omega_0 = 2070 \text{ GHz}$ or $9 \mu\text{m}$ wave length in the infrared spectrum of the dissolved oxygen in silicon, taking from literates^{10, 11, 12]}. The force constant of vibration mode Q3 for Si-O bond is $K=0.074 \text{ N/m}$. It can be seen from Figure 6 that the larger is force constant K and the less is the effective mass m_e in some one stealth material, then the higher is intrinsic frequency ω_0 which is suitable for used in the range of infrared light. Contrarily, these stealth materials with the less force constant K and the larger effective mass m_e are suitable for used in the range of microwave.

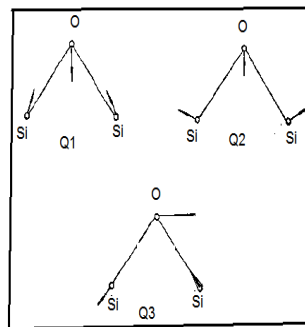


Figure 8: Normal Vibration Modes Q1,Q2,Q3

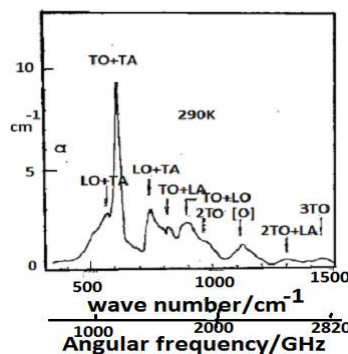


Figure 9: Infrared Absorption Spectrum for with Si-O Bong^{10]} for Silicon^{13]}

2.5.4 The Original for Vibrators and the Intrinsic Frequency ω_0 in Stealth Materials

2.5.4.1 Lattice Atom Chain Vibration in Diatomic Ionic Crystals^{3]}

For the lattice atom chain vibration in diatomic ionic crystals, there are two intrinsic frequencies i.e. respectively for either optical wave O or acoustic wave A. The number of waves depends upon the atom number in a primary crystal cell. Both of them can also be divided into longitudinal L and transverse T wave. Wherein

$$\omega^2 \approx \frac{K_1(m_1 + m_2)}{2m_1m_2} = \omega_o^2 \tag{24}$$

For the optical branch O.

$$\text{When } m_1 \gg m_2, \omega_o^2 \approx \frac{K_1}{2m_2} \quad (25)$$

$$\text{And another frequency is } \omega^2 \approx \frac{K_1}{2(m_1 + m_2)} \frac{a^2}{\lambda^2} = \omega_A^2 \quad (26)$$

For the acoustical branch A, where λ is its wave length with $\lambda \gg 0$.

$$\text{When } m_1 \gg m_2, \omega_A^2 \approx \frac{K_1}{2m_1} \frac{a^2}{\lambda^2} \quad (27)$$

And $\omega_A^2 \approx \frac{K_1}{2m_1}$ with $\lambda_{\min} = a$. a is the primary cell length. So $\omega_o \gg \omega_A$. The vibration direction and

propagation direction for longitudinal wave are consistent. However, those of the transverse waves are mutually perpendicular. For the optical frequency wave O, the adjacent positive and negative ions vibrate in the opposite direction so as to give rise the electric dipole moment with a high frequency and to absorb infrared energy. For acoustic waves A, the adjacent positive and negative ions vibrate with a low frequency in the same direction so it does not give rise electric dipole moment to absorb infrared energy. $\omega_o \approx \sqrt{K_1/2m_2}$ For optical frequency wave O depends upon K_1 and m_2 , for example, the highest angular frequency 983GHz (i.e. wavenumber 523 cm^{-1}) in the intrinsic continuous spectra of pure silicon lattice. A higher frequency $\omega = \omega_i + \omega_j \dots$ with the combination beyond two optical waves O, even adding one acoustic wave A can be got, called multiple phonon combinations, such as $h\omega_i/2\pi + h\omega_j/2\pi + \dots$ so as to absorb infrared light energy $h\omega/2\pi = h\omega_i/2\pi + h\omega_j/2\pi + \dots$, here h is Planck constant. Figure 9 shows multiple phonon combination peaks LO+TA, TO+TA, 3TO occur in infrared absorption spectrum of silicon¹³¹. The angular frequencies of them are all higher than 983GHz. The higher is probability of multiple phonon combinations; the better is the effect to absorb infrared light energy as stealth materials.

2.5.4.2 Local Mode in Lattice Atom Chain Vibration^{15, 16, 17]}

If introducing impurities in the lattice, because the mass M_2 of impurity atoms are different from that of M_1 matrix atoms and the force constants of vibration are also different, so that the vibration status of crystal changes. Then outside dynamic vibration band in the pure crystal exists a new allowable vibration band, be called local mode vibration status. The intrinsic frequency of the local mode depends on the ratio of the impurity atoms to matrix atoms. When $M_2 < M_1$, if M_2/M_1 is greater than a certain threshold, then the characteristic frequency of local mode $\omega_L > \omega_M$, ω_M is the highest frequency in a pure crystal intrinsic spectra. When the $M_2 > M_1$, then the characteristic frequency of the impurity atom vibration $\omega_L < \omega_M$. This frequency occurs in the vicinity of the lattice vibration due to resonance, the bigger is the M_2/M_1 , the lower is ω_L , and the sharper is the resonance peak. For example, when the light boron doped in silicon, the local vibration mode of boron can be observed. Local mode frequencies of boron doped silicon is at the wavenumber 642 and 618 cm^{-1} , more than the highest frequency 523 cm^{-1} , in the intrinsic continuous spectra of pure silicon lattice.

As atoms in the crystal structure with diamond type are all electrically neutral, so perfect crystals cannot give rise single phonon absorption. But in case of presence of impurities in crystals, impurity atoms destroy periodicity of lattice so

as to alter the electronic structure around it, causing the first-order term dipole. On the one hand, the first order of electric dipole moments due to impurity vibration can lead to optical absorption; on the other hand, the infrared light absorption can also occurs in the range of local mode frequency. Because of a lower frequency for micro-wave, its absorption mainly arise from the mechanism by local mode vibration with a lower force constant K_1 and a heavily impurity atom M_2 , please to see section 2.9.4. .

2.5. The Relationship between the Imaginary Part in the Complex Dielectric Constant and Absorption Coefficient When the Sample is Irradiated by Electromagnetic Wave

Polarization strength due to N vibrator number i.e. electrons in samples is²¹

$$\tilde{P} = Nqx = \frac{Nq^2 E e^{i\omega t}}{m_e (\omega^2 - \omega_0^2 - i\nu\omega)} \quad (28)$$

\tilde{P} -Polarization strength, N-Vibrator number with charge q in unit volume ($1/\text{cm}^3$); thus, obtaining:

$$\tilde{\epsilon} = 1 + \frac{\tilde{P}}{\epsilon_0 E e^{i\omega t}} = 1 + \frac{Nq^2}{\epsilon_0 m_e (\omega_0^2 - \omega^2 - i\nu\omega)} \quad \tilde{\epsilon} = (n - ik)^2 = 1 + \frac{Nq^2}{\epsilon_0 m_e (\omega_0^2 - \omega^2 - i\nu\omega)} \quad (29)$$

$\tilde{\epsilon}$ -Complex dielectric constant of materials; ϵ_0 -vacuum dielectric constant. It can be seen from formula $\tilde{\epsilon} = (n - ik)^2$ (11): the complex dielectric constant $\tilde{\epsilon}$ can be divided into real and imaginary parts: $\tilde{\epsilon} = \epsilon' - i\epsilon''$, that is to say

$$\epsilon' = n^2 - k^2, \quad \epsilon'' = 2nk \quad (30)$$

$$n^2 - k^2 - 1 = \frac{(\omega_0^2 - \omega^2)Nq^2}{\epsilon_0 m_e ((\omega_0^2 - \omega^2)^2 - i\nu^2 \omega^2)} = \frac{(\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)^2 - i\nu^2 \omega^2} A \quad (31)$$

$$2nk = \frac{\omega\nu}{(\omega_0^2 - \omega^2)^2 + \omega^2\nu^2} \frac{Nq^2}{\epsilon_0 m_e} = \frac{\omega\nu}{(\omega_0^2 - \omega^2)^2 + \omega^2\nu^2} A \quad (32)$$

$$A = \frac{Nq^2}{m_e \epsilon_0} \quad (34)$$

where $\omega_0 = \sqrt{K/m_e}$, A is a quantity with a dimension of Hz^2 , i.e. sec^{-2} but different from ω_p^2 (expression 8) with m^* .

$$\alpha = 2nk\omega/nc = \frac{1}{nc} \frac{\omega^2\nu}{(\omega_0^2 - \omega^2)^2 + \omega^2\nu^2} \frac{Nq^2}{\epsilon_0 m_e} = \frac{1}{nc} \frac{\omega^2\nu}{(\omega_0^2 - \omega^2)^2 + \omega^2\nu^2} A \quad (35)$$

The following graph shows the relationship of A among N and m_e .

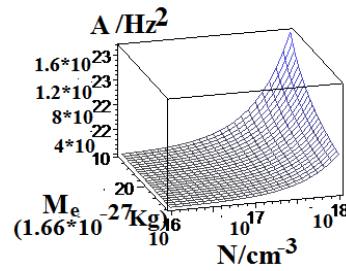
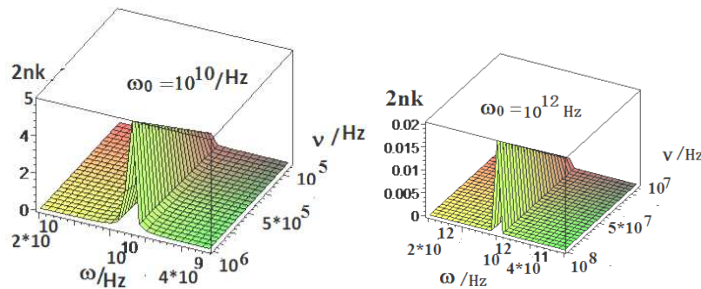


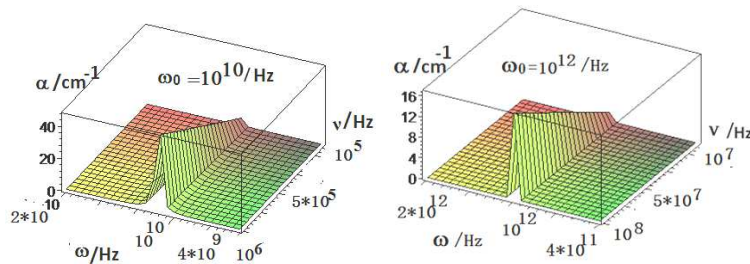
Figure 10: Relationship of A among N and m_e

The following graphs 11 and 12 show the relationship of $2nk$ and α among ω and ν at definite ω_0 with $A=10^{22} \text{ Hz}^2$ (i.e. $m_e = 10 \times 1.66 \times 10^{-27} \text{ Kg}$, $N=10^{16}/\text{cm}^3$)



at definite $\omega_0=10^{10}/\text{Hz}$ at definite $\omega_0=10^{12}/\text{Hz}$

Figure 11: Relationship of $2nk$ among ω and ν at Definite ω_0 with $A=10^{22}\text{Hz}^2$.



at definite $n=4, \omega_0=10^{10}/\text{Hz}$ at definite $n=4, \omega_0=10^{12}/\text{Hz}$

Figure 12: Relationship of α among ω and ν at Definite ω_0 with $A=10^{22} \text{ Hz}^2$

It can be seen that when $\omega = \omega_0$, a sharp absorption peak occurs, called resonance between the incidence electromagnetic wave and vibration of lattice at ω_0 .

$$\text{When } \omega > \omega_0 \gg \nu, \alpha \approx \frac{1}{nc} \frac{\nu}{\omega^2} \frac{Nq^2}{m_e \epsilon_0} = \frac{1}{nc} \frac{\nu}{4\pi^2 (c/\lambda)^2} \frac{Nq^2}{m_e \epsilon_0} = \frac{\nu}{4\pi^2 nc^3} \frac{Nq^2}{m_e \epsilon_0} \lambda^2 \tag{36}$$

$$\text{When } \omega < \omega_0 \gg \nu, \alpha = 2nk\omega / nc \approx \frac{1}{nc} \frac{\omega^2 \nu}{\omega_0^4} \frac{Nq^2}{\epsilon_0 m_e} = \frac{1}{nc} \frac{4\pi^2 \nu}{\omega_0^4} \frac{Nq^2}{\epsilon_0 m_e} \frac{1}{\lambda^2} \tag{37}$$

Where λ is wave length, ω -angular frequency for the used incidence electromagnetic wave irradiation apart from intrinsic angular frequency ω_0 . This is the normal case with $\omega > \omega_0$ or $\omega < \omega_0$, thus $\alpha \propto \lambda^2$ or $\alpha \propto \lambda^{-2}$. The graphs of

relationship α among ω , λ and N for expression (35) are respectively shown in Figure 15-a and b.

2. 6 The Experimental Relationship between Wave Absorption Index k and the Imaginary Part in the Complex Dielectric Constant When the Sample is Irradiated by Electromagnetic Wave

Known from above, electromagnetic wave absorption index k is associated with the imaginary part $\epsilon'' = 2nk$ of the complex permittivity $\tilde{\epsilon}$. Then 3mm thick absorbing coatings were made of ITO powder mixed with epoxy resin E44 at 7.7vol%, 15.8vol% volume ratio. The experimental results of imaginary part ϵ'' in the range of 2.6~18GHz was shown in figure 13.

We can see from Figure 13, the absorption peak is around 4.51GHz for 15.8vol% ITO coating; the absorption peak is near 11GHz for 7.7vol%, ITO coating. Sn doped In₂O₃ (i.e. ITO) has both free electrons and O²⁻ ions in the crystals, thus forming an electric dipole.

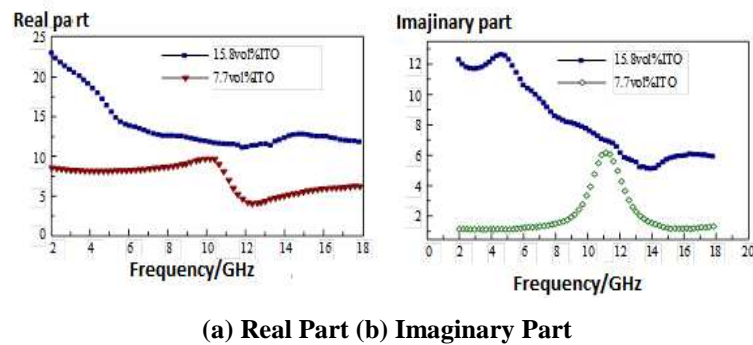


Figure 13: Variation of the Complex Dielectric Constant with Frequency for 7.7vol%, 15.8vol% ITO

Electric dipole orientation changes and moves with the external electric field, inducing dielectric loss, due to influences such as lattice resistance, at this time to play a role of microwave absorption.. The vibration frequency of the electric dipole is high, both in the microwave and infrared regions; ITO is also a stealth material with good performance for either the microwave or infrared light absorbing.

2.7: The lattice atoms in non-polar crystals are not charged, atom vibration in crystal does not cause changes of the first order of electric dipole moments, so does not appear light absorption. Therefore we try not to choose non polar crystal coating as stealth materials. However, non-polar crystals due to atomic distortion deformation also can cause the electric dipole moment^{18]} to cause light absorption. For example, although silicon is a non-polar crystal, 10 infrared absorption peaks appear in its infrared absorption spectrum (see Figure 9) within a frequency range from 0.8 to 3×10^3 GHz, so non-polar crystal is also could be selected for stealth materials or coating.

2. 8: The Infrared Absorption Band

Absorption band refers to an integration area overall whole frequency distribution of absorption coefficient: $\int \alpha d\omega$. As far as stealth materials, the higher is absorption coefficient, the stronger is absorption band. This is hopeful to stealth materials. Vibrational frequencies and the numbers of oscillators in sample are more abundant, with it more infrared absorption peaks to occur, then total absorption band area is broaden, the stealth effect is better.

2.9: Infrared Absorption in Semiconductors

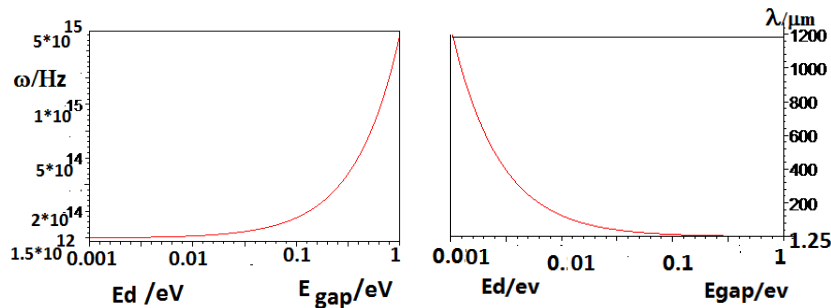
2.9.1: The Intrinsic Absorption

The energy transition of the electron in valence band to conduction band of the semiconductor after absorption of a photon is called the intrinsic absorption. The photon energy $h\omega/2\pi$ should be larger than the band gap width. That is to say, the light wavelength should not be more than **1200 μm** for the intrinsic absorption, as shown in Figure 14.

Table 3 shows the band gap width for different crystals. To make the irradiated light being absorbed, the best choice is such as semiconductor materials with narrow forbidden gap width for stealth material or coating, but needs to consider the economic costs.

Table 3: The Forbidden Gap Width for Different Crystals

Crystals	ZnO	GaAs	InSb	Si	Ge	TeO2
gap width (eV)	3.2	1.42	0.225	1.16	0.77	



(a) Angular Frequency ω (b) Wave Length λ

Figure 14: The Wave Spectrum Arisen from Absorption Due to Energy Level Transition

2.9.3. Impurity Absorption Due to Their Energy Levels

The electrons at donor levels transit to the excited state energy level or the conduction band, and the holes at the acceptor energy transit to the excited state or the valence band after absorbing a photon, called impurity absorption. There is a long wave limit λ for impurity absorption spectra as shown in Figure 14:

$$\lambda = ch/E_D \text{ and } \omega = 2\pi c/\lambda = 2\pi E_D/h \tag{38}$$

where, E_D —donor impurity ionization energy;

ω —The angular frequency of light;

h —Planck constant (6.63×10^{-34} J.s)

Because the impurity ionization energy is very small with an order of mV, so the long wave limit in the absorption spectrum should be at the far infrared band, this also has a certain relation with stealth materials used for microwave band as $\lambda > 1000\mu\text{m}$, as shown in Figure 14..

2.9.4. The Free Carrier Absorption

Free carriers in semiconductors will receive energy under the action of the radiation field and then pass it to the lattice, making electromagnetic energy to attenuate. Free carriers are arisen from the doping impurity (different from impurity absorption due to energy level transition in above section 2.9.3), both of it and the adjacent atom form vibrators

with an electric dipole. The first order of electric dipole moments induces absorption of the infrared light, when these vibrators move with the external electric field. In this case expression (35) could be used for calculation of the absorption coefficient of materials.

Thus, the absorption coefficient α and $2nk$ of materials are proportional to the product of electron concentration N (free electron number in unit volume) and the square of wavelength or it's reciprocal (see expression 36), taking $\nu=0.001\text{GHz}$, $\omega_0=10\text{ GHz}$, $m_e=10.2\times 1.66\times 10^{-27}\text{ Kg}$ as an example, shown in Figure 15. It can be seen that when the electron concentration above $10^{18}/\text{cm}^3$, called heavily doping, then most of the irradiating infrared light are absorbed for $\omega>\omega_0$. They are not transparent through them for the infrared light with a larger α as $\lambda>30\mu\text{m}$. However, when $\omega<\omega_0$, α is contrarily proportional to the wave length λ and not vary with doping concentration N for the same λ unlike as the case of $\omega>\omega_0$. This case of $\omega<\omega_0$ is not hopeful to occur for that choosing stealth materials with a little natural frequency $\omega_0 = \sqrt{K/m_e}$, i.e. less K and larger m_e , because when even $N > 10^{19}/\text{cm}^3$, α is still little.

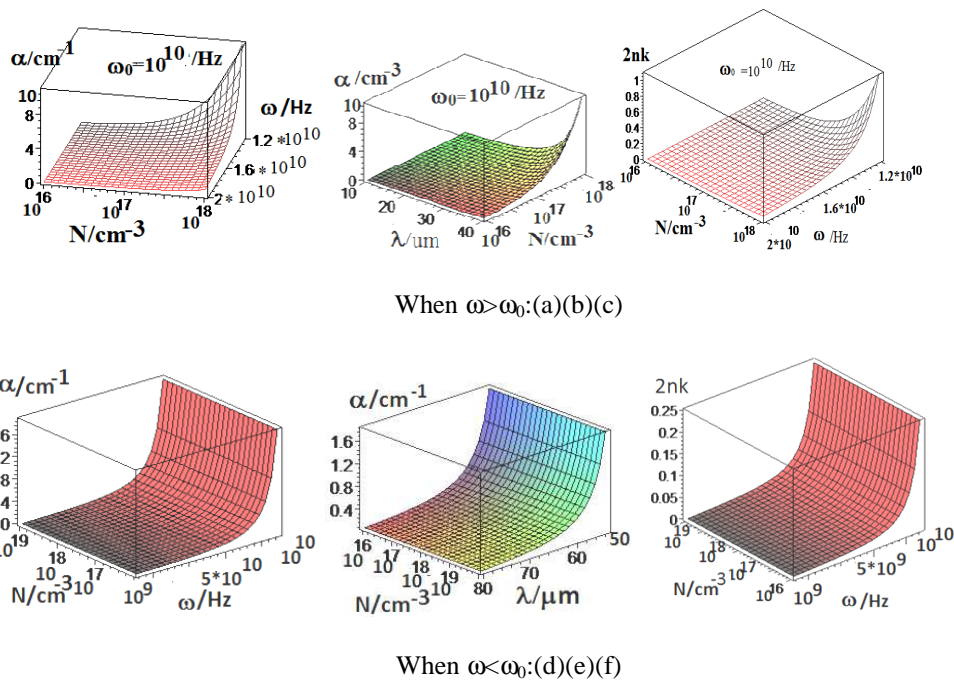


Figure 15: Relationship of Absorption Coefficient and $2nk$ (c、f) among N and Wave Angular Frequency ω (a、d), Length λ (b、e) Both with $\omega_0 = 10^{10}\text{Hz}$

Short metal fiber, barium titanate ceramic, conductive polymer and conductive graphite powder are of high conductive materials, wherein free carrier concentration is high and their price is not expensive, they are the preferred materials for infrared and microwave band absorption. The absorption coefficient α is positively related to square of wavelength and α is also related to the absorption index, hence undoubtedly they are stealth materials for microwave band. As a summary, Table.4 shows the absorption mechanisms in the different wave lengths.

Table 4: Absorption Mechanisms in the different Wave Lengths

Wave Length $\lambda/\mu\text{m}$	Absorption Mechanism	Wave Band
0.1~3	Intrinsic absorption	Infrared
5~100	lattice atom chain vibration	Infrared
100~300	Free carrier absorption	Infrared
300~>1000	Impurity absorption due to energy levels including their exciting status levels	Microwave

2.10: The Infrared Light Trapping Effect for a Film Made of ZnO Crystals¹⁹⁾

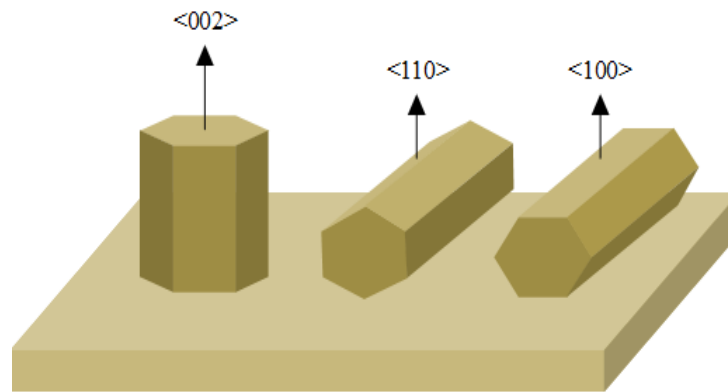


Figure 16: A schematic Graph for the Lying Six Prismatic ZnO Crystals on the Membrane

Six prismatic structure crystals of ZnO have two possible states for the bare surface. A vertical light to the thin film lying with ZnO crystals will suffer reflection from (002) bare surface. And it will also suffer reflection from the (100) bare surface. However, (110) surface is not a bare surface, the vertical light to thin film will not suffer reflection from (110) surface. That is to say, ZnO six prismatic crystals should be fabricated to lie down a membrane as like as the intermediate case, shown in Figure 16, because the intermediate case can generate light trapping effect for this thin film. Light trapping film is like frosted glass with the occurrence of diffuse scattering, so as to most of incident infrared light transiting through the transparent film into the underlying metal or graphite layers and be absorbed to produce stealth effects.

The light trapping ZnO films were fabricated using metal-organic chemical vapor deposition (MOCVD) technique on a high light absorption membrane. The structure of the system is shown in Figure 17. The Ar gas (99.995% purity) as the carrier gas, carrying the two sources out of a steam bubble enters the reaction chamber. Zinc source is zinc ethyl DEZn (99.99% purity), the oxygen source is use of pure water H₂O.

The relation between the light trapping property and the revealed X-ray diffraction peaks of the crystal for the deposition film is studied to focus on influence of the substrate temperatures, source flow and reaction pressure on properties of ZnO films so as to obtain a desired light trapping structure.

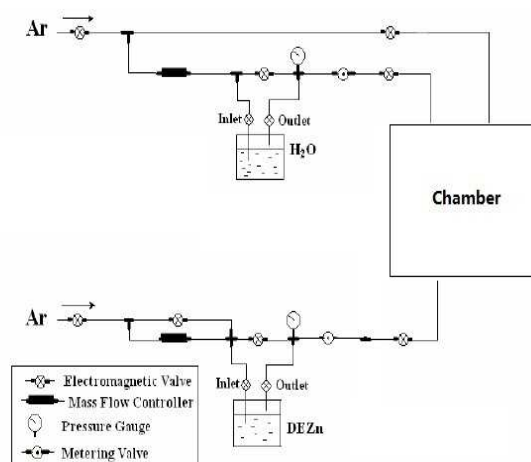


Figure 17: The Structure of the MOCVD System for Fabricating ZnO Membrane

In addition, such as a wave-absorbing structure developed by Japan, was formed from a surface layer (composed of carbon fiber and silicon nitride fiber and a resin), matched layer (composed of zirconia, alumina, silicon nitride or other ceramic) and bottom layer (made of metal film or carbon fiber fabric), which may be an example of application of the infrared light trapping in stealth technology, similar to the ZnO crystal film for the infrared light trapping.

2.11 Optical or Electromagnetic Wave Propagation in the Photonic Crystal and Application in Infrared Stealth Technology ^{20, 21, 22, 23]}

Photonic crystals refer to materials with a special photonic band gap. Photonic crystals were proposed independently in 1987 by S. John ^{20]} and E. Yablonovitch ^{21]}, which are formed by dielectric constant periodic arrangement with different refractive index for the artificial micro structure. E. Yablonovitch proposed that such a medium could be made by carving out voids in a transparent material to create a periodic structure, analogous to a crystal lattice, with the material and the voids having different indices of refraction (different speeds of light), as like as an energy “band gap” between the valence and the conduction electrons. Just as electrons with energies in the band gap cannot exist in a semiconductor, so light with frequencies in the electromagnetic band gap would not exist in the proposed structure. In each case, the periodic structure leads to destructive wave interference (electron waves or electromagnetic fields) that leads to the gap.

In trying to make a photonic crystal, E. Yablonovitch ^{22]} worked with microwaves, rather than visible or infrared light, because their longer wavelengths allowed him to develop periodic designs with spacing on the scale of a few millimeters. After testing many different possibilities, the first structure with a photonic band gap, consisting of spherical holes arrayed throughout a block of plastic in a face-centered cubic (fcc) pattern. It ought to block radiation in all directions. A structure possessed a true photonic band gap—one that prevented radiation in all directions.

In recent years, photonic crystals have been used for several purposes, such as optical fibers that in some cases confine light more effectively than traditional fibers.

Because of the dielectric constant with a periodic space, causing periodic spatial variation of refractive index thus exists the emergence of "photonic frequency band gaps" ^{23]}. Light or electromagnetic wave with a frequency in the band

gap cannot propagate in photonic crystals that can avoid the light radiation to arise by it, so that itself spontaneous radiation due to heating photonic crystals is resisted and not found by enemy combat aircrafts.

If introduction of defects in the photonic crystal induces the corresponding energy levels of defects in frequency band gaps, called localizing photons²⁰⁾, then this incident electromagnetic wave with corresponding frequency can transit through photonic crystals and not blocked by them, showing low reflectance characteristics, that has important significance for stealth materials with infrared broad band so as to realize the compatibility of infrared and laser stealth.

3. CONCLUSIONS AND SUMMARY

This paper introduces rules of the wave reflection and absorption of the electromagnetic wave in solids, applied to principles of the stealth technology for radar and infrared light as well as laser, to elucidate the mechanism of the effect of light trapping.

Stealth materials are often composed of multilayer's: Surface film is a transparent one, with low reflectivity either for radar and infrared light or for laser.

Based on the above discussion shows that the concentration of free electrons in the material as surface film or the core should be low, so that the plasma resonance frequency is reduced, so as to expand the frequency range toward low-end, being helpful to reduce the reflectivity of microwave radar, also reduce reflectivity over the full frequency range after the dielectric constant is reduced. The porosity in the material is higher, the reflectance is also lower. For the infrared light, a light trapping film such as ZnO as the surface film can reduce the reflectivity.

The bottom should be an absorption film for radar or infrared light, the concentration of free electrons and polar vibrator concentration or their charges in the underlying material should be high. We should choose such as micro wave stealth materials with a little natural frequency $\omega_0 = \sqrt{K/m_e}$, i.e. less K and larger m_e for vibrators in them to prevent the case of $\omega < \omega_0$ to occur, when even $N > 10^{19}/\text{cm}^3$, α is still little. Because of micro wave frequency is at most $\omega = 20\text{GHz}$ with $\lambda = 1\text{mm}$.

In addition, using narrow gap semiconductors as bottom layer, so as to increase the intrinsic edge wavelength, is advantageous to increase the infrared wavelength range to absorb the infrared light.

The research of photonic crystal just started, the opinions in this paper about their applications in stealth materials are not mature.

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