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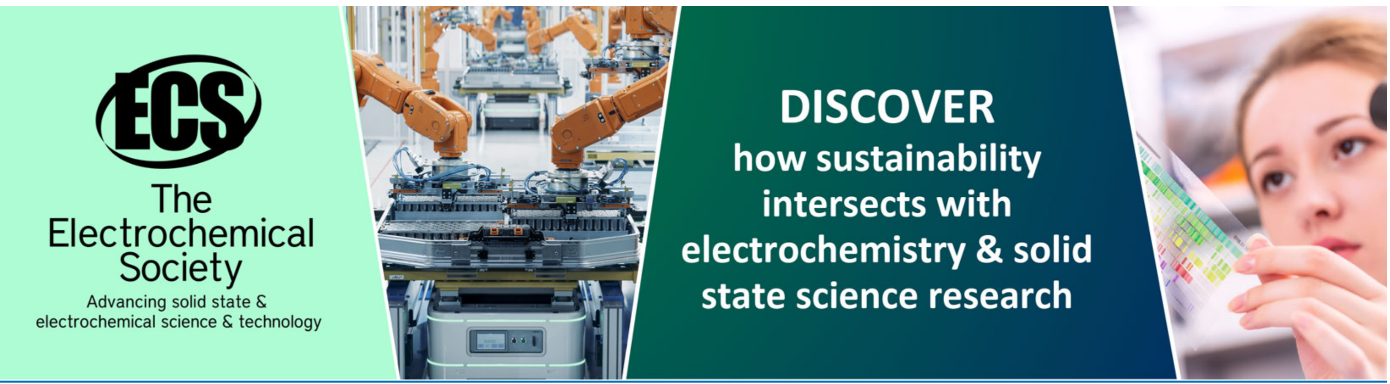

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Conductivity tensor in semiconductor with the presence of a laser field and an electromagnetic wave field for the case of scattering on ionized impurities

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Abstract. There are a lot of studies on semiconductors and in semiconductors also appear many dynamic effects, from the research results that have many applications in science and technology. Conductivity tensor is a familiar concept in physics in general and semiconductors in particular, but research on scattering on ionized impurities is still limited. This paper presents the influence of laser field and electromagnetic waves on conductivity tensor for the case of scattering on ionized impurities in semiconductor. The particle system is placed in an electromagnetic wave field and a laser field. Using quantum kinetic equations for electrons in semiconductor under the action of an electromagnetic wave field, a laser field, the conductivity tensor is calculated with case of scattering on ionized impurities. Conductivity tensor depends on the frequency of the laser field, the laser field amplitude, the electromagnetic wave frequency and typical parameters for semiconductor system. With different frequency bands, the dependence of tensor conductivity on the frequency is different, and the special conductivity tensor is strongly dependent on the amplitude of the laser field but depends very little on its frequency. The results will be plotted and discussed with GaAs semiconductor case and compared with studies for different scattering cases.

1. Introduction

In theoretical physics research, the dynamic properties of semiconductors have been studied by many authors because it helps provide much information about this material [1-3]. There are many different methods to solve the problem, one of the methods used is the method using quantum kinetic equations. Electromagnetic waves and laser fields affect many dynamic effects and conductivity tensor, the electromagnetic wave carries energy and momentum so it has an impact on the scattering processes of particles [4-6]. Electron – ionized impurities scattering in the presence of electromagnetic and laser fields can be added by the absorption and radiation of photons.

Conductivity tensor is very important for materials, it involves a lot of kinetic processes and specifically solves the problem of electrical phenomena. In this work, the particle system is placed in an electromagnetic wave field, a laser field. Using quantum dynamic equations for electrons, calculate the conductivity tensor for the case of scattering on ionized impurities in semiconductor. Conductivity tensor is a function of the electromagnetic frequency, frequency and amplitude of the laser field.

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Dependence of conductivity tensor on electromagnetic wave frequency, laser field frequency, laser field amplitude will be plotted and discussed with GaAs semiconductor case.

2. Calculating conductivity sensor with the presence of a laser radiation field

Consider the carrier system placed in a linearly polarized electromagnetic field:

$$\begin{cases} \vec{E}(t) = \vec{E}(e^{-i\omega t} + e^{i\omega t}) \\ \vec{H} = [\vec{n}, \vec{E}(t)] \end{cases}$$

and a laser field: $\vec{F}(t) = \vec{F}\sin\Omega t$

where $\vec{n}$ is the unit vector along the direction of wave propagation; ω is the electromagnetic wave frequency; Ω is the laser field frequency, F is the laser field amplitude

The quantum kinetic equation for electron in semiconductor [7-12]:

$$\frac{\partial f(\vec{p},t)}{\partial t} + \left(e\vec{E}(t) + \omega_H \left[\vec{p}, \vec{h}(t)\right], \frac{\partial f(\vec{p},t)}{\partial \vec{p}} \right) = \\ = 2\pi \sum_{\vec{q}} M(q) \sum_{l=-\infty}^{+\infty} J_l^2(\vec{a},\vec{q}) \left[f(\vec{p}+\vec{q},t) - f(\vec{p},t) \right] \delta\left(\varepsilon_{\vec{p}+\vec{q}} - \varepsilon_{\vec{p}} - l\Omega\right) \tag{1}$$

with $\hbar = 1$; $f(\vec{p},t)$ is distribution function; $\vec{h}(t) = \frac{\vec{H}(t)}{H}$ is the unit vector in the magnetic field direction; $\vec{p}$ is momentum of electron; $\varepsilon_{\vec{p}} = \frac{(\vec{p})^2}{2m}$; $\varepsilon_{\vec{p}+\vec{q}} = \frac{(\vec{p}+\vec{q})^2}{2m}$; $\omega_H = \frac{eH}{mc}$; $\vec{a} = \frac{e\vec{F}}{m\Omega^2}$; $J_l^2(\vec{a},\vec{q})$ is the Bessel function of real argument; $\vec{q}$ is momentum of phonon. For simplicity, we limit the problem to the case of $l = 0, \pm 1$:

$$J_0^2 \approx 1;\ J_\pm^2 \approx \frac{(\vec{a},\vec{q})^2}{4} \tag{2}$$

$$f(\vec{p},t) = f_0(\varepsilon_{\vec{p}}) + f_1(\vec{p},t)\ f_0(\varepsilon_{\vec{p}}) = \theta(\varepsilon_F - \varepsilon_{\vec{p}});\ f_1(\vec{p},t) = -\vec{p}\vec{\chi}(t) f_0'(\varepsilon_{\vec{p}}) \tag{3}$$

$$f_0'(\varepsilon) = \frac{\partial f_0(\varepsilon)}{\partial t};\ f_1(\vec{p},t) = f_1(\vec{p})e^{-i\omega t} + f_1^*(\vec{p})e^{i\omega t};\ f_1(\vec{p}) = -\vec{p}\vec{\chi} f_0'(\varepsilon_{\vec{p}}) \tag{4}$$

$$\vec{\chi}(t) = \vec{\chi}e^{-i\omega t} + \vec{\chi}^* e^{i\omega t};\ \vec{\chi} = \frac{e}{m}\vec{E}\frac{\tau(\varepsilon)}{1 - i\omega\tau(\varepsilon)} \tag{5}$$

$$\frac{\partial f(\vec{p},t)}{\partial t} = \frac{\partial}{\partial t}\left[f_0(\vec{p}) + f_1(\vec{p})e^{-i\omega t} + f_1^*(\vec{p})e^{i\omega t} \right] = -i\omega f_1(\vec{p})e^{-i\omega t} + i\omega f_1^*(\vec{p})e^{i\omega t} \tag{6}$$

Multiply both sides Eq. (1) by $-\frac{e}{m}\vec{p}\delta(\varepsilon - \varepsilon_{\vec{p}})$ and then sum over $\vec{p}$ to get expression:

$$-\frac{e}{m}\sum_{\vec{p}} \vec{p} \left[\frac{\partial f(\vec{p},t)}{\partial t} - \left(e\vec{E}(t) + \omega_H \left[\vec{p}, \vec{h}(t)\right], \frac{\partial f(\vec{p},t)}{\partial \vec{p}} \right) \right] \delta(\varepsilon - \varepsilon_{\vec{p}}) = \\ = -\frac{e}{m}\sum_{\vec{q}} M(q) \sum_{\vec{p}} \vec{p} \left[2\pi \sum_{l=-\infty}^{+\infty} J_l^2(\vec{a},\vec{q}) \left[f(\vec{p}+\vec{q},t) - f(\vec{p},t) \right] \delta\left(\varepsilon_{\vec{p}+\vec{q}} - \varepsilon_{\vec{p}} - l\Omega\right) \right] \delta(\varepsilon - \varepsilon_{\vec{p}}) \tag{7}$$

Calculate the left side of equation (7):

The first term $-\frac{e}{m}\sum_{\vec{p}} \vec{p} \frac{\partial f(\vec{p},t)}{\partial t} \delta(\varepsilon - \varepsilon_{\vec{p}}) = -i\omega\vec{R}(\varepsilon)e^{-i\omega t} + i\omega\vec{R}^*(\varepsilon)e^{i\omega t}$ (8)

with
$$\vec{R}(\varepsilon) = -\frac{e}{m}\sum_{\vec{p}}\vec{p}f_1(\vec{p})\delta(\varepsilon-\varepsilon_{\vec{p}})\,; \tag{9}$$

$$\vec{R}^*(\varepsilon) = -\frac{e}{m}\sum_{\vec{p}}\vec{p}f_1^*(\vec{p})\delta(\varepsilon-\varepsilon_{\vec{p}}) \tag{10}$$

The second term: $\frac{e}{m}\sum_{\vec{p}}\vec{p}\left(e\vec{E}(t),\frac{\partial f(\vec{p},t)}{\partial\vec{p}}\right)\delta\left(\varepsilon-\varepsilon_{\vec{p}}\right) = \vec{Q}\left(e^{-i\omega t}+e^{i\omega t}\right)$ (11)

with
$$\vec{Q} = \frac{e^2}{m}\sum_{\vec{p}}\left(\vec{E},\frac{\partial f(\vec{p},t)}{\partial\vec{p}}\right)\vec{p}\delta\left(\varepsilon-\varepsilon_F\right) \tag{12}$$

The third term:
$$\begin{aligned}&\frac{e}{m}\sum_{\vec{p}}\vec{p}\left(\omega_H\left[\vec{p},\vec{h}(t)\right],\frac{\partial f(\vec{p},t)}{\partial\vec{p}}\right)\delta\left(\varepsilon-\varepsilon_{\vec{p}}\right) = \\ &= \omega_H\left[\vec{R}(\varepsilon)+\vec{R}^*(\varepsilon),\vec{h}\right]+\omega_H\left[\vec{R}(\varepsilon),\vec{h}\right]e^{-2i\omega t}+\omega_H\left[\vec{R}^*(\varepsilon),\vec{h}\right]e^{2i\omega t}\end{aligned} \tag{13}$$

with
$$\vec{R}(\varepsilon) = -\frac{e}{m}\sum_{\vec{p}}\vec{p}f_1(\vec{p})\delta\left(\varepsilon-\varepsilon_{\vec{p}}\right) \tag{14}$$

Calculate the right side of equation (7):
Consider the case that l = 0:

$$\begin{aligned}&-\frac{e}{m}\sum_{\vec{p}}2\pi\sum_{\vec{q}}M(q)\vec{p}J_0^2(\vec{a},\vec{q})\left[f(\vec{p}+\vec{q},t)-f(\vec{p},t)\right]\delta\left(\varepsilon_{\vec{p}+\vec{q}}-\varepsilon_{\vec{p}}\right)\delta\left(\varepsilon-\varepsilon_{\vec{p}}\right) = \\ &= -\frac{1}{\tau(\varepsilon)}\left(\vec{R}(\varepsilon)e^{-i\omega t}+\vec{R}^*(\varepsilon)e^{-i\omega t}\right)\end{aligned} \tag{15}$$

Consider the case that $l = \pm 1$:

$$\begin{aligned}&-\frac{e}{m}\sum_{\vec{q}}M(q)\sum_{\vec{p}}\vec{p}\left[2\pi\sum_{l=\pm1}J_{\pm1}^2(\vec{a},\vec{q})\left[f(\vec{p}+\vec{q},t)-f(\vec{p},t)\right]\delta\left(\varepsilon_{\vec{p}+\vec{q}}-\varepsilon_{\vec{p}}\pm\Omega\right)\right]\delta\left(\varepsilon-\varepsilon_{\vec{p}}\right) = \\ &= \vec{S}(\varepsilon)e^{-i\omega t}+\vec{S}^*(\varepsilon)e^{i\omega t}\end{aligned} \tag{16}$$

With
$$\begin{aligned}\vec{S}(\varepsilon) = -\frac{e}{m}2\pi\sum_{\vec{q}}M(q)\frac{(\vec{a},\vec{q})^2}{4}\sum_{\vec{p}}f_1(\vec{p})\times \\ \times\left[\delta\left(\varepsilon_{\vec{p}+\vec{q}}-\varepsilon_{\vec{p}}-\Omega\right)+\delta\left(\varepsilon_{\vec{p}+\vec{q}}-\varepsilon_{\vec{p}}+\Omega\right)\right]\times \\ \times\left[\left(\vec{p}+\vec{q}\right)\delta\left(\varepsilon-\varepsilon_{\vec{p}+\vec{q}}\right)-\vec{p}\delta\left(\varepsilon-\varepsilon_{\vec{p}}\right)\right]\end{aligned} \tag{17}$$

Put the expressions (8), (11), (13), (15), (16) on (7), then unify the terms of both sides to get the system of equations:

$$\left[-i\omega+\frac{1}{\tau(\varepsilon)}\right]\vec{R}(\varepsilon) = \vec{Q}+\vec{S} \tag{18}$$

$$\left[i\omega+\frac{1}{\tau(\varepsilon)}\right]\vec{R}^*(\varepsilon) = \vec{Q}+\vec{S} \tag{19}$$

from equations (19) obtained:

$$\vec{R}(\varepsilon) = \frac{\tau(\varepsilon)}{1 - i\omega\tau(\varepsilon)}(\vec{Q} + \vec{S}) \quad (20)$$

with
$$\vec{S} = \frac{e^2 n}{m}\left[\lambda\delta(\varepsilon - \Omega) - A\delta(\varepsilon - \varepsilon_F)\right]\frac{\tau(\varepsilon)}{1 - i\omega\tau(\varepsilon)}\vec{E} \quad (21)$$

n is particle density; m is the effective mass of electron; $e = 1.6*10^{-19}C$; $\tau(\varepsilon)$ is the momentum relaxation time in absence of laser radiation.
Consider the case of scattering on ionized impurities:

$$\lambda_{ij} = -\frac{16\beta}{15\tau(\Omega)G(\xi)}\left(\delta_{ij} - \frac{a_{0i}a_{0j}}{2}\right); \quad (22)$$

$$A_{ij} = \frac{\beta}{6\tau(\Omega)G(\xi)}\left[\frac{4}{3}\left(\frac{\varepsilon_F}{\varepsilon}\right)^{3/2} - \frac{K_{FT}^2}{20m\Omega}G(\xi)\phi(k)\right] - \frac{\beta K_{FT}^2}{10\tau(\varepsilon_F)m\Omega}\phi(k)a_{0i}a_{0j} \quad (23)$$

with
$$\tau(\varepsilon) = \tau(\varepsilon_F)\left(\frac{\varepsilon_F}{\varepsilon}\right)^{1/2};\ \beta = \frac{e^2F^2}{m\Omega^3};\ \vec{a}_0 = \frac{\vec{a}}{a};\ \xi = \frac{8m\Omega}{K_{FT}^2};\ k = \frac{2m\varepsilon_F}{K_{FT}^2} \quad (24)$$

$$G(\xi) = \ln(1+\xi) - \frac{\xi}{1-\xi};\ \phi_K = \frac{1}{G(4k)}\left[\frac{k^2}{2(1+k)} - G(k)\right] \quad (25)$$

K_{FT} is the reciprocal
At time t = 0, the density of current [7]:

$$\vec{j}(t=0) = \int(\vec{R}(\varepsilon) + \vec{R}^*(\varepsilon))d\varepsilon = \vec{j}_1 + \vec{j}_1^*$$
$$= \frac{e^2 n}{m}\frac{\tau(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\left\{\mathbf{1} + \lambda\frac{\tau(\Omega)\left[1 - \omega^2\tau(\Omega)\tau(\varepsilon_F)\right]}{1+\omega^2\tau^2(\Omega)} + \right. \quad (26)$$
$$\left. - A\frac{\tau(\varepsilon_F)\left[1-\omega^2\tau^2(\varepsilon_F)\right]}{1+\omega^2\tau^2(\varepsilon_F)}\right\}2\vec{E}$$

with
$$\vec{j}(t=0) = \sigma\vec{E}(t=0) = \sigma 2\vec{E} \quad (27)$$

so
$$\sigma_{ij}(\omega) = \frac{e^2 n}{m}\frac{\tau(\varepsilon_F)}{1+\omega^2\tau^2(\varepsilon_F)}\left\{\delta_{ij} + \frac{\tau(\Omega)\left[1-\omega^2\tau(\Omega)\tau(\varepsilon_F)\right]}{1+\omega^2\tau^2(\Omega)}\lambda_{ij} + \right.$$
$$\left. - \frac{\tau(\varepsilon_F)\left[1-\omega^2\tau^2(\varepsilon_F)\right]}{1+\omega^2\tau^2(\varepsilon_F)}A_{ij}\right\} \quad (28)$$

δ_{ik} is the Kronecker symbol

This is the expression for calculating the tensor conductivity in a semiconductor in the presence of an electromagnetic wave and a laser field for scattering on ionized impurities.

3. Numerical results and discussion

From the conductivity tensor's expression, a graph of the dependence of the conductivity tensor on the laser field frequency, laser field amplitude, and electromagnetic wave frequency will be plotted. The semiconductor examined here is the GG semiconductor. The parameters used in the calculations are as follows [7-12]: m = 0,067m_0 (m_0 is the mass of free electron); ε_F = 50meV; $\tau(\varepsilon_F) \sim 10^{-11}s^{-1}$; $n = 10^{23} m^{-3}$; E = 10^6 V/m.

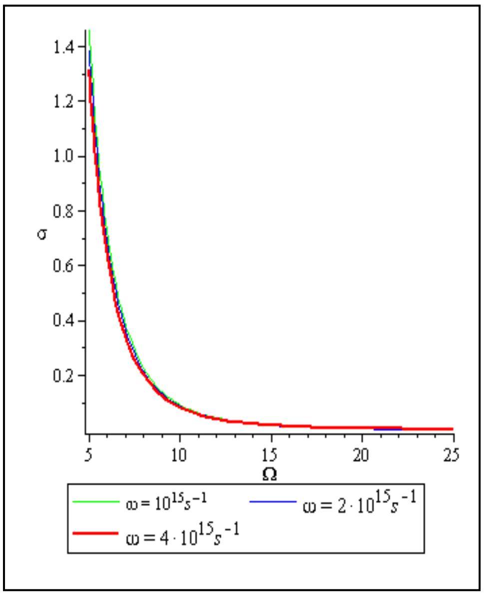

Figure 1. The dependence of σ on the frequency Ω of the laser radiation with different values of ω when Ω at low frequencies

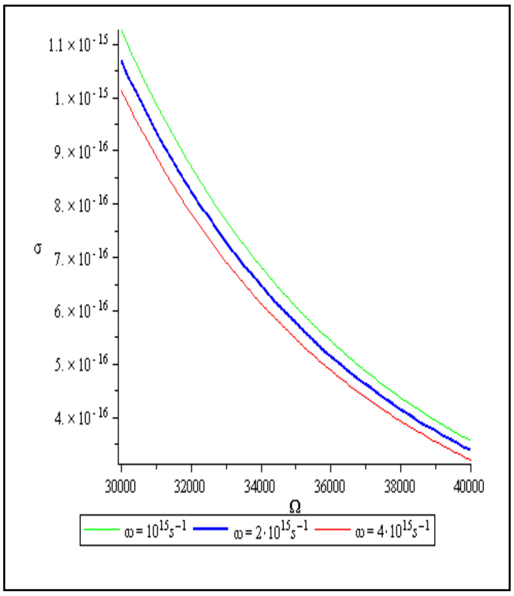

Figure 2. The dependence of σ on the frequency Ω of the laser radiation with different values of ω when Ω at frequencies 3.10^4 to $4.10^4 s^{-1}$.

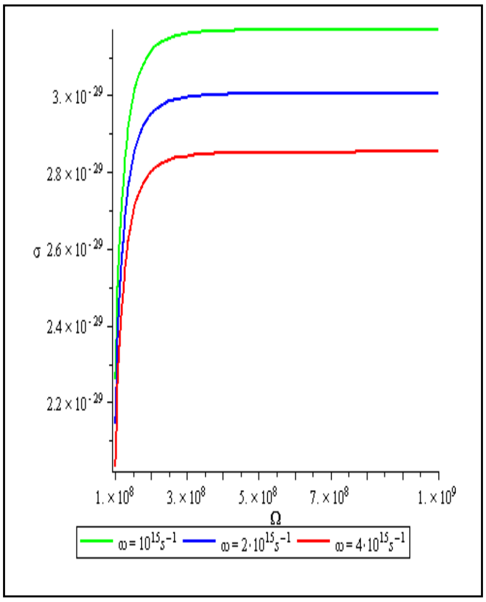

Figure 3. The dependence of σ on Ω of with different values of ω when Ω at frequencies greater than 10^8 s^{-1}.

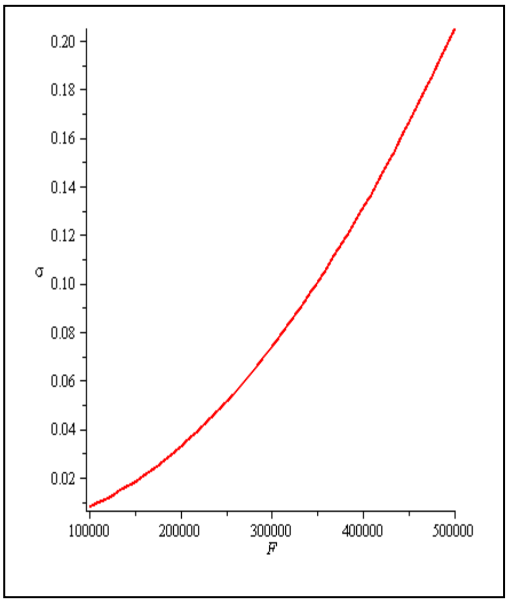

Figure 4. The dependence of σ on the amplitude F of the laser radiation.

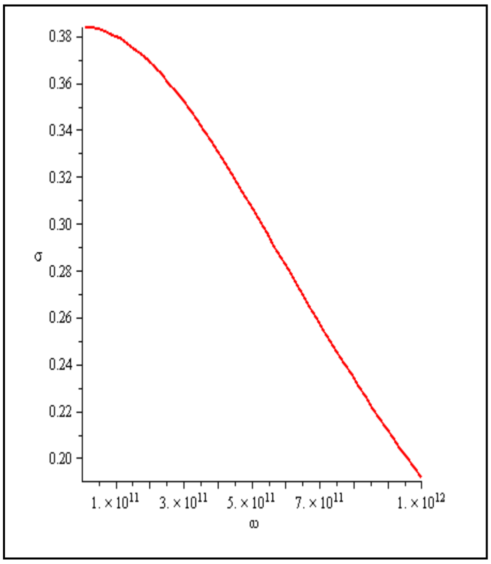

Figure 5. The dependence of σ on the frequency ω of the electromagnetic wave at frequencies 10^{11} s^{-1} to 10^{12} s^{-1}.

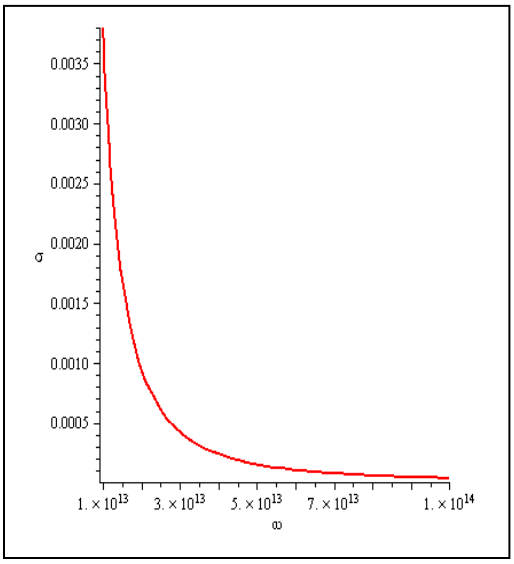

Figure 6. The dependence of σ on the frequency ω of the electromagnetic wave at frequencies greater than 10^{13} s^{-1}.

Figure 1 shows that as the laser field frequency increases, the conductivity tensor will decrease and decrease very quickly at first and then very little, the plot is almost parallel to the horizontal axis. At the higher frequency shown in figure 2, the conductivity is very small and continues to decrease rapidly. At even higher frequencies represented by figure 3, the conductivity tensor increases rapidly as the frequency increases but as the frequency continues to increase the conductivity tensor almost does not increase anymore and reaches a stable value.
Figure 4 shows the dependence of the conductivity tensor on the laser field amplitude, the graph shows that as the laser field amplitude increases, the conductivity tensor also increases, the change of the conductivity tensor with the very laser field amplitude obviously, at a larger amplitude the faster tensor increases as the amplitude increases.
Figure 3 and 4 show the dependence of the conductivity tensor on the frequency of the electromagnetic wave. At frequencies between $10^{11}s^{-1}$ and $12^{12}s^{-1}$ tensor conductivity decreases as frequency increases. At frequencies between $10^{13}s^{-1}$ and $10^{13}s^{-1}$, the conductivity tensor decreases rapidly, then decreases very little and gradually reaches a stable value.
Above is a graph showing the dependence of the conductivity tensor on the characteristic parameters of the electromagnetic wave and the laser field from which the effects of the two fields can be seen on the conductivity tensor.

4. Conclusions

The paper studied the effects of electromagnetic waves and laser fields on conductivity tensor in semiconductors for the case of scattering on ionized impurities. The expression shows the dependence of conductivity tensor on laser field frequency, laser field amplitude and electromagnetic wave frequency. In addition, the conductivity tensor depends on the characteristics of the semiconductor system such as: particle density, the effective mass of electron, the momentum relaxation time in absence of laser radiation. The paper also investigated and plotted the dependence of conductivity tensors on laser field frequency, laser field amplitude and electromagnetic wave frequency. The plot shows the dependence of the conductivity tensor on the frequency of the laser field and the electromagnetic wave is nonlinear. There are frequency ranges that increase conductivity tensor, but there are also frequency ranges that reduce conductivity tensor. The laser field amplitude affects the conductivity tensor greatly, but at any amplitude the laser field amplitude increases the conductivity tensor very quickly.

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