Internal Photoeffect under the Action of Ultrashort Electromagnetic Pulses: Dependence of Pulse Duration

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Abstract— The paper is devoted to theoretical analysis of internal photoeffect induced by ultrashort electromagnetic pulses (USP). The total probability (during all time of USP action) of photo-excitation of impurity state into the energy band in a semiconductor matrix was calculated. We also calculated the spectral probability of total photo-excitation for various pulse durations and analyzed the obtained spectra.

It has been found that internal photoeffect induced by USP has specific features which differ from characteristics of this phenomenon under the action of long electromagnetic pulses.

1. INTRODUCTION

Development of techniques for generating ultrashort electromagnetic pulses (USP) of different shapes and durations makes relevant theoretical studies of the interaction of such pulses with matter.

In particular, the investigation of interaction of such pulses with semiconductors is of big practical importance, that may lead to new effects and opportunities of their applications. In our work all results were obtained for gallium arsenide (GaAs) doped with manganese (Mn) impurity. In general case all these results can be extended to other types of semiconductors.

2. CALCULATIONS

The calculations are based on the expression for probability of photo-induced processes derived in paper [1] in the frame of perturbation theory:

$$W = \frac{c}{(2\,\pi)^2} \int\limits_0^\infty \sigma\left(\omega'\right)\, \frac{\left|F\left(\omega'\right)\right|^2}{\hbar\,\omega'}\, d\omega'. \tag{1}$$

Here $\sigma(\omega')$ is the cross-section of the impurity-band photo-excitation, $F(\omega')$ is Fourier transform of the electric field strength in the pulse, c is light velocity.

In the contrast to the paper [2] where only carrier distribution function in the valence band was considered, in the present work main attention is given to the dependence of excitation probability (W) on the pulse duration τ for various values of carrier frequency (ω) of the pulse.

We consider the absorption of several types of USP:

$$E_{cor}\left(t\right) = \mathrm{Re}\left[-i\,E_0\,\frac{\left(1 + i\,t/\omega\,\tau^2\right)^2 + 1\Big/(\omega\,\tau)^2}{1 + 1\Big/(\omega\,\tau)^2}\,\exp\left(-t^2/2\,\tau^2\right)\,\exp\left(i\,\omega\,t + i\varphi\right)\right] \tag{2}$$

$$E_{\sin}(t,\tau) = \frac{\sqrt{2}E_0}{\sqrt[4]{\pi}}\frac{t}{\tau}\exp\left(\frac{-t^2}{2\tau^2}\right) \tag{3}$$

$$E_{\cos}(t,\tau) = \frac{2E_0}{\sqrt{3}\sqrt[4]{\pi}}\left(1 - \left[\frac{t}{\tau}\right]^2\right)\exp\left(\frac{-t^2}{2\tau^2}\right) \tag{4}$$

It is so called corrected Gaussian pulse (CGP) (2) [3], sine- (3) and cosine (4) wavelet pulses. Such pulses have no constant component in their spectrum in contrast with traditional Gaussian pulse. It should be noted that the presence of a constant component for ultrashort pulse durations leads to unphysical results.

Let us calculate the spectral probability of photo-excitation. In accordance to the law of energy conservation we can write the following expression:

$$\hbar\omega' = I_{th} + \varepsilon \tag{5}$$

where ω' — frequency of monochromatic component of CGP, I_{th} — excitation threshold approximately equal to 0.1 eV [4], ε — is hole energy in the valence band.

So, with the use of (5) we can obtain from the expression (1):

$$\frac{dW}{d\varepsilon} = \frac{c}{(2\pi)^2} \int_0^{\infty} \sigma\left(\omega'\right) \frac{\left|E(\omega')\right|^2}{\hbar\omega'} \delta\left(\hbar\omega' - I_{th} - \varepsilon\right) d\omega' \tag{6}$$

Due to the presence of δ-function in the integral (6), the expression for spectral probability of photo-excitation can be rewritten as:

$$\frac{dW}{d\varepsilon} = \frac{c}{(2\pi)^2\hbar} \sigma\left(\frac{I_{th}+\varepsilon}{\hbar}\right) \frac{\left|E\left(\frac{I_{th}+\varepsilon}{\hbar}\right)\right|^2}{I_{th}+\varepsilon} \tag{7}$$

In all calculations used cross-section $\sigma(\omega')$ calculated from experimental data taken from [6]. Electric field strength E_0 for all types of pulses equals to $5 \cdot 10^{-3}$ at.u.

3. RESULTS

In Figure 1 the dependencies of total probability of photo-excitation are shown as a function of pulse duration at different carrier frequencies ω of corrected Gaussian pulse. It is shown that for

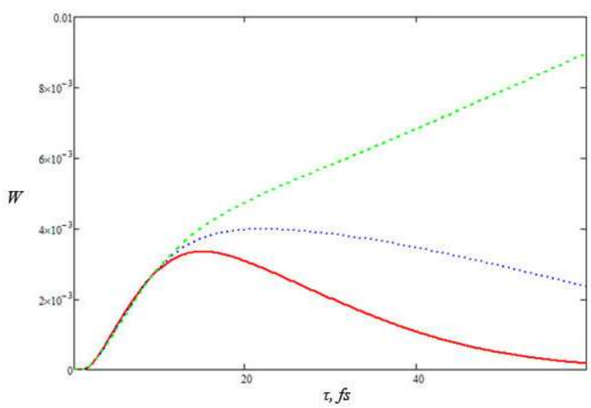

Figure 1: Total probability of photo-excitation as a function of pulse duration at different carrier frequencies of incident CGP. The solid line: $\omega = 0.08$ eV; dotted line: $\omega = 0.09$ eV; dashed line: $\omega = 0.1$ eV.

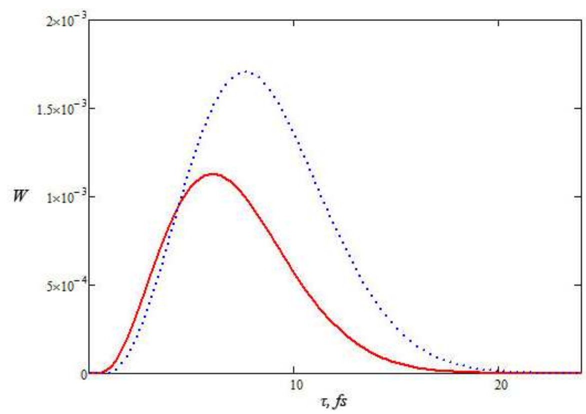

Figure 2: Total probability of photo-excitation for wavelet pulses. The solid line: sine wavelet; dotted line: cosine wavelet.

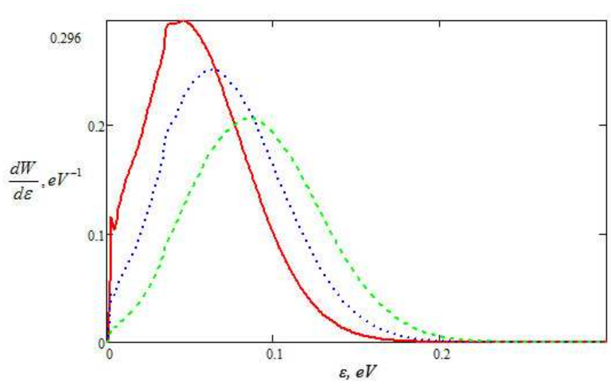

Figure 3: Spectral probability of total photo-excitation as a function of hole energy at different carrier frequencies of CGP and pulse duration 10 fs. The solid line: $\omega = 0.09$ eV; dotted line: $\omega = 0.12$ eV; dashed line: $\omega = 0.15$ eV.

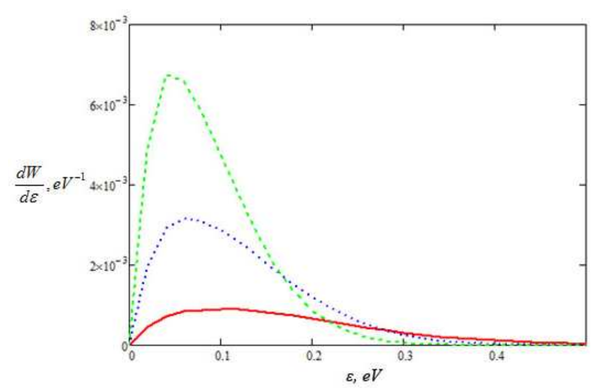

Figure 4: Spectral probability of total photo-excitation as a function of hole energy for sine wavelet at different pulse durations. The solid line: $\tau = 2$ fs; dotted line: $\tau = 3$ fs; dashed line: $\tau = 4$ fs.

frequency ω smaller than the excitation threshold (I_{th}), the dependence $W(\tau)$ looks as a curve with a maximum $W(\tau \to \infty) \to 0$. On the contrary for $\hbar\omega' > I_{th}$, excitation probability rises with the increase of pulse duration and transforms to the linear dependence at sufficiently large values of parameter τ.

In the case of sine- and cosine wavelet pulses, the results are shown on Figure 2. Qualitatively the dependencies for both pulses are similar, but the curve corresponding to the cosine wavelet has a maximum shifted to longer pulses durations and has larger probability.

In Figure 3 spectral probability of total photo-excitation is shown as a function of the hole energy at different carrier frequencies of CGP and pulse duration 10 fs. We can see that the grater central frequency of CGP the less amplitude at maximum of all dependencies and they are shifting to the higher hole energy.

Figure 4 presents the spectral probability of total photo-excitation as a function of the hole energy for sine wavelet at different pulse durations. We can see that the increasing of pulse duration lead to increasing of amplitude of spectral probability.

4. CONCLUSIONS

We have calculated and analyzed the total and spectral probability of photo-excitation of Mn impurity state in GaAs matrix under the action of various USP as a function of pulse duration — $W(\tau)$ and $dW/d\varepsilon$. Particular attention was given to near threshold range of carrier frequency of the pulse. It was shown that the character of $W(\tau)$ in the case of corrected Gaussian pulse is strongly dependent on carrier frequency ω. So for $\hbar\omega' < I_{th}$ the function $W(\tau)$ is the curve with a maximum which goes to zero with the increase of τ. The position of maximum shifts into long-pulse region as $\eta\omega$ approaches to the threshold. When $\hbar\omega' > I_{th}$, the total probability of photo-excitation monotonically increases and for sufficiently long CGP it transforms into linear function of τ as in the case of monochromatic excitation. Another situation takes place for wavelet pulses without carrier frequency. Namely, the total probability $W(\tau)$ has maximum at $\tau = 5$–7 fs and always approaches to zero for large values of pulse duration.

Spectral probability as a function of the hole energy in the valence band has maximum which position shifts to a higher energy with the increase of CGP carrier frequency and the decrease of duration of wavelet pulses. The maximum value of spectral probability is higher for CGP in comparison with wavelet pulse case.

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