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Optical spanner based on the transfer of spin angular momentum of light in semiconductors

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ABSTRACT

An optical spanner is a light beam that can exert a torque on a microscopic object. When a circularly polarized beam irradiates semiconductors, the output light becomes partially circularly polarized. Thus the total angular momentum of the light beam is changed, which leads to a torque, creating an optical spanner on the semiconductor. In this letter, we investigate this kind of optical spanner in detail, and its electric and magnetic control are discussed.

1. Introduction

Optical tweezers are powerful tools for manipulating microscopic objects [1] including living cells. In addition to holding the trapped object in place by optical tweezers, it is also possible to rotate it utilizing an optical spanner [2], which uses a laser beam to exert a torque on the microscopic object. The optical spanner is based on the transfer of the angular momentum from the light to the microscopic object [3]. To form an optical spanner is of interest and has attracted a number of theoretical and experimental researchers [4,5]. Beth [6] first proposed using transfer of the angular momentum of light to achieve the angular manipulation of macroscopic objects. Simpson and co-workers designed optical spanners with Laguerre–Gaussian modes [7]. Friese et al. demonstrated optically driven motors on transparent birefringent particles of calcite trapped by optical tweezers experimentally [8]. The phenomena of light induced rotation of absorbing microscopic particles due to the transfer of angular momentum from light to the material was observed by utilizing elliptically polarized beams [9] or beams with helical phase structure [10]. The analogous phenomenon of rotation of metallic particles induced by the orbital angular momentum of the light beam was reported by O'Neil and Padgett [11]. Chen et al. found an electrically and magnetically controlled optical spanner with Pockels and Faraday effects in the optically active medium [12]. And Galstyan et al. carried out light-driven molecular motor by controlling the transfer of the light angular momentum to nematic-liquid-crystal molecules [13]. In this letter, we will report an electrically and magnetically controllable optical spanner on the semiconductor crystal.

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2. Theory and discussion

Our basic idea of this optical spanner is: when a circularly polarized beam irradiates the semiconductors, spin polarized electrons and holes are generated by light excitation, then these spin-aligned electrons and holes recombine to emit partially circularly polarized luminescence. For each left (right) handed circularly polarized photon possesses a spin angular momentum of $-\hbar$ ($\hbar$) [14], the total angular momentum of the light beam is changed, which is transferred to the medium according to the law of conservation of angular momentum. Under the condition of continuous laser excitation, the spins of electrons, holes, impurities and nucleus are in equilibrium, only phonons could bear the transferred angular momentum from photons, so this angular momentum is finally transmitted to crystal lattice to create a torque, forming an optical spanner on the semiconductor. To discuss this optical spanner, our major work is to investigate the changed spin angular momentum between the output light and the incident beam. For this, we first give a simple introduction of the interaction between light and semiconductors. Fig. 1 shows the selection rules for absorption and emission of light of direct band-gap semiconductors, such as GaAs [15]. Here we consider only the states in conduction band (CB), heavy hole band (HH) and light hole band (LH). The split-off band is ignored and we assume that there is no light excitation from that band.

Then we begin our discussion. For simplicity, we assume that the pump beam is left-handed circularly polarized. From Fig. 1 we can see when the semiconductor is excited by the left-handed circularly polarized light, there are electron transmissions of $|3/2, +3/2\rangle \rightarrow |1/2, +1/2\rangle$ and $|3/2, +1/2\rangle \rightarrow |1/2, -1/2\rangle$ to create electron- and hole-spins. As well known, the degree of circular

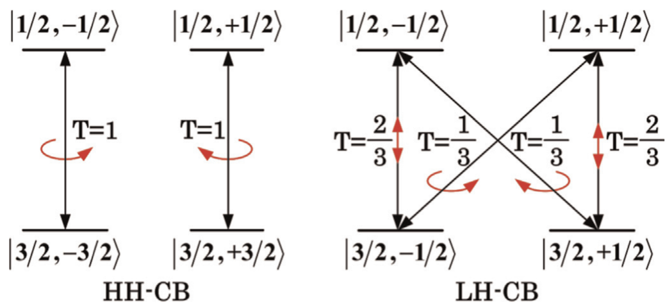

Fig. 1. Selection rules and relative transition rate T for optical transitions corresponding to interband transitions of HH-CB and LH-CB. The red lines with arrows indicate the light polarization. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

polarization of the partially circularly polarized emission light is associated with these excited spins [16], therefore, to know the spin angular momentum carried by the output light we should investigate the dynamics of these spins. We further consider the material is p-doped semiconductors. We know that in p-doped semiconductors the population of light excited polarized holes are far less than the population of the unpolarized thermal equilibrium holes, so the recombination probability of a photo-excited hole is negligible compared with a thermal equilibrium hole, which means that the emission light is determined by the electron spin polarization rather than hole spins in p-doped semiconductors. Therefore, we should only pay attention to the spin alignment of the conduction-band electrons.

For this, we introduce N_+ and N_- to indicate the population of the spin-up and down electrons under the continuous laser excitation. Taking the spin relaxation, the generation and the recombination into account, the rate equations governing the population change of N_+ and N_- are given by [17]

$$\frac{dN_+}{dt} = -\frac{N_+}{\tau} - \frac{N_+}{T_s} + \frac{N_-}{T_s} + \frac{N_{0+}}{\tau}, \tag{1}$$

$$\frac{dN_-}{dt} = -\frac{N_-}{\tau} - \frac{N_-}{T_s} + \frac{N_+}{T_s} + \frac{N_{0-}}{\tau}, \tag{2}$$

where τ is the lifetime and T_s is the spin-alignment relaxation time of conduction-band electrons. And $\tau_{es} = T_s/2$ is the so called spin relaxation time. N_{0+}/τ and N_{0-}/τ are introduced to represent the generation rate of spin-up and down electrons via light excitation, corresponding to electrons transition of $|3/2, +3/2\rangle \rightarrow |1/2, +1/2\rangle$ and $|3/2, +1/2\rangle \rightarrow |1/2, -1/2\rangle$, respectively. It easy to know that $N_{0+} = 3N_{0-}$ due to the different transition rates from the light-and heavy-hole valance bands. The sum of Eqs. (1) and (2) is the decay of the total electron population in the conduction band:

$$\frac{d(N_+ + N_-)}{dt} = -\frac{(N_+ + N_-)}{\tau} + \frac{(N_{0+} + N_{0-})}{\tau}, \tag{3}$$

and the rate of change of the difference of the spin-up and spin-down electrons populations is

$$\frac{d(N_+ - N_-)}{dt} = -\frac{(N_+ - N_-)}{\tau} - \frac{(N_+ - N_-)}{\tau_{es}} + \frac{(N_{0+} - N_{0-})}{\tau}. \tag{4}$$

With the steady-state conditions $d(N_+ + N_-)/dt = 0$ and $d(N_+ - N_-)/dt = 0$, we can solve Eqs. (3) and (4) to obtain $N_+ + N_- = N_0$ and $N_+ - N_- = \tau_{es}N_0/(2\tau_{es} + 2\tau)$, where $N_0 = N_{0+} + N_{0-}$, so that

$$N_+ = N_0/2 + \tau_{es}N_0/(4\tau_{es} + 4\tau), \tag{5a}$$

$$N_- = N_0/2 - \tau_{es}N_0/(4\tau_{es} + 4\tau). \tag{5b}$$

Then according to the selection rules and relative transition rates for emission of light, the ratio of the luminescence intensities of two circular polarizations is

$$\lambda = \frac{L_+}{L_-} = \frac{N_+ + 2N_-}{2N_+ + N_-} = \frac{5\tau_{es} + 6\tau}{7\tau_{es} + 6\tau}, \tag{6}$$

where L_+ and L_- are the intensities of (σ_+) right- and (σ_-) left-handed circularly polarized luminescence, respectively. So, the total spin angular momentum of light transmitted per second is

$$M_s = -2\hbar\frac{L_+}{L_+ + L_-}\frac{N_0}{\tau} = -\hbar N_0\frac{5\tau_{es} + 6\tau}{6\tau_{es}\tau + 6\tau^2}, \tag{7}$$

where N_0/τ represents the population of electrons excited per second, which is equal to the population of photons absorbed per second. It is related to the power of the input laser on per unit area W as $N_0/\tau = \alpha WLS/\hbar\omega$. Here, $\hbar\omega$ is the single photon energy, α is the optical absorption of the material, S is the absorption cross section, and L is the thickness of the semiconductors. Therefore, Eq. (7) could be rewritten as

$$M_s = -\frac{\alpha WLS}{\omega}\left(1 - \frac{\tau_{es}}{6\tau_{es} + 6\tau}\right). \tag{8}$$

According to Eq. (8), a larger torque can be achieved by using a high-intensity light beam since it is proportional to intensity, and the torque is related to the lifetime and the spin relaxation time of the conduction band electrons. Furthermore, the frequency of excitation light could also affect the torque, for both the denominator of Eq. (8) contains frequency and the optical absorption is associated with frequency.

The induced torque will drive the microscopic semiconductor crystal to rotate. The equation of rotational motion for it is

$$I\frac{d^2\varphi}{dt^2} + \gamma\frac{d\varphi}{dt} = M_s, \tag{9}$$

where I is the moment of inertia of the microscopic semiconductor crystal about its axis and γ is the drag torque coefficient. As the excitation light is continuous laser, we have steady-state condition $d^2\varphi/dt^2 = 0$. Then we can obtain the expression of angular velocity

$$\Omega = \frac{M_s}{\gamma} = -\frac{\alpha WLS}{\gamma\omega}\left(1 - \frac{\tau_{es}}{6\tau_{es} + 6\tau}\right). \tag{10}$$

According to Eq. (10), we could give a specific estimation on the angular velocity of a microscopic GaAs particle in water for realistic temperature and excitation intensity. For this, we first assume that the shape of the GaAs micro meter size particle is cylinder with thickness (L=10 μm) and radius (R=5 μm). So the drag torque coefficient is $\gamma = 32\eta R^3/3$ [18], where η is the viscosity of the fluid, which is 0.8937 mPa s [19] for water at 25 °C, thus we have $\gamma = 1.1916 \times 10^{-18} N$ m s. Moreover, for our estimation we use parameters: τ = 175 ps, τ_{es} = 100 ps, $\hbar\omega$ = 1.4 eV, $\alpha \approx 10^3$ cm^{-1} and the laser power I = 100 mw, which leads to $\omega = 2.13 \times 10^{15}\ s^{-1}$ and $W = I/\pi R^2 = 1.27 \times 10^9$ w m^{-2}. Then it is very easy to obtain the angular velocity $\Omega = 37\ rad\ s^{-1}$.

Until now, we have shown an optical spanner based on the transfer of spin angular momentum of light in semiconductors. In the following, we will further investigate the control of this optical spanner with Pockels effect and Hanle effect.

We first discuss its electric control with Pockels effect. Our control method is utilizing an electro-optic crystal to manipulate the degree of circular polarization (P) of the pump light by Pockels effect, which is shown in Fig. 2(a). Here, $P = (I_- - I_+)/(I_- + I_+)$ with $I_\pm$ is the light intensity of $\sigma_\pm$. When P is manipulated, we can obtain