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# Long-range pair transport in graded band gap and its applications

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## Abstract

The transport of electron–hole pairs in graded band gap of mixed crystal semiconductors is examined. It is estimated that a pair can be transferred for about 30 μm within its lifetime in the band gap gradient of 1 meV/μm in the low-temperature AlGaAs quantum well. Various opto-electronic devices by means of the pair transport are proposed. As one of exciting applications, the author proposes the quantum up-converter, where incoherent low-energy photons are converted to high-energy photons.

*Keywords:* Exciton transport; Drift; Graded band gap; Up-converter

## 1. Introduction

The transport of excitons in indirect-gap semiconductors and of those whose radiative recombination is dipole- and/or spin-forbidden has been studied well [1]. In order to drift the excitons, graded band gap is realized by applying the graded pressure onto the crystals. It has been observed that the excitons travel for hundreds of micrometers within their extremely long lifetimes of microseconds to milliseconds. The control of band gap by pressure is, however, not suitable for realization of sophisticated opto-electronic devices, because it is not flexible enough to handle local band gap energy at arbitrary positions in arbitrary ways. In addition, these semiconductors are not luminescent.

In luminescent semiconductors, such the long-range transport has not been studied very well, probably because lifetimes of excitons are short. However, there are some suggestive reports. For example, in the GaAs quantum well, the isotropic diffusion of excitons with a diffusion length of 2 μm was spatially resolved [2]. Short-range, but very efficient pair transfer was observed in the graded band gap of the AlGaAs-based graded index separate confinement heterostructure (GRINSCH), where the exciton transfer for 200 nm occurs within 20 ps of the time resolution [3].

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In this paper, the author proposes a flexible method for long-range transport of neutral electron–hole pairs (excitons). As one of possible applications of the transport, the author presents the quantum up-converter, where low-energy photons are efficiently converted to high-energy photons. Numerical analysis of the up-converter will be given. Related experimental practices will be reported elsewhere.

## 2. Proposed Idea

Proposal: *Built-in band gap gradient due to the graded stoichiometric composition of mixed crystal semiconductors is to be realized. As one of the method for this purpose, the focused ion beam (FIB) injection technique will be adapted for injecting constituent atoms, to shift local stoichiometric composition.*

Since the FIB apparatus allows the injection of elements to arbitrary position of target materials in the nanometer preciseness, it is useful to realize the in-plane gradient for two-dimensionally integrated devices. Subsequent annealing will be indispensable for recovering crystallinity.

A possible range of the pair transport is estimated as follows. We shall consider an AlGaAs quantum well. By injecting aluminium and/or gallium ions into the well, the local band gap energy in the QW will be shifted. We assume the band gap gradient of $1\,\mathrm{meV}/\mu\mathrm{m}$, the exciton mass of $m_x = m_e + m_h = 0.517 m_0$ (the value for GaAs), and the exciton lifetime of $\tau_{\rm life} = 1\,\mathrm{ns}$. The phase relaxation time of the exciton is assumed to be $T_2 = 2h/\Gamma = 8.3\,\mathrm{ps}$ from the homogeneous line width in the GaAs quantum well at low temperature [4]. Treating a pair as a classical particle placed in the potential of $E_g(r)$, the drift distance within the lifetime is estimated as

$$v_{\rm drift}\tau_{\rm life} = \nabla E_g T_2 m_x^{-1} \tau_{\rm life} = 28\,\mu\mathrm{m}.$$

This length is large enough to wire between functional nanostructures, because such nanostructures can be designed in a smaller dimension than the drift range. The transport range increases when the band gap gradient is strengthened, but decreases due to the phonon scattering when the temperature is raised. It is noted that the influences of the alloy scattering and the impurity scattering are not included in the estimate. The drift distance is estimated as a rough standard of the transportation range for the discussion below.

## 3. Possible applications

The long-range transport makes various applications possible. There are various elementary functions by semiconductor nanostructures, such as light absorption, light emission, charge separation, pair injection, nonlinear responses, spin control, phase transition, catalytic reactions, and so on, where electron–hole pairs play crucial roles. By transferring pairs between more than two such functional parts, it is possible to realize combined new functions and even integrated devices, which have not been considered up to now. As examples, three applications are schematically shown in Fig. 1. A very simple example is the combination of an absorbing part and an emitting part (a), which enables to design absorption and emission

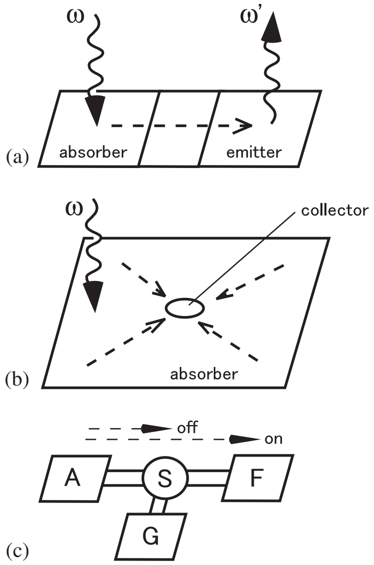

Fig. 1. Examples of possible application of the pair transport. Dotted arrows represent the drift of pairs. Wavy arrows represent incoming and outgoing photons. (a) A combined device of an absorber and an emitter. (b) A photon capturing system. (c) A configuration of conditional devices.