Nanomaterials

Quantum dots for optoelectronics

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Abstract: We review the the development of nanostructured materials for exercising control over and improving the properties of materials for optoelectronic devices. In particular, the use of quantum dots as the active element of amplifiers and lasers is discussed as well as the new opportunities arising from the discrete level structure of quantum dots.

Technological developments within crystal growth and processing have made it possible to fabricate structures in which the available electronic as well as photonic states can be controlled. This is achieved by modifying the material composition on the micro- to nanometer scale. Thus, a photonic crystal structure incorporated into the material by a periodic modulation of the refractive index, in 1, 2 or 3 dimensions with periodicity on the order of the optical wavelength in the material, allows realizing a forbidden frequency gap as well as engineering the dispersion of electromagnetic wavepropagation in the structure. Line defects in the crystal can be used to create optical waveguides, while point defects realize optical cavities, which may reach very high quality factors corresponding to long storage times of the photons.

Photonic crystal structures allow smaller and more densely integrated structures compared to conventional wavguide technology, but minimum dimensions are still on the order of a wavelength. The use of surface plasmon polaritons bound to the interface of a metal and a dielectric is another way of guiding electromagnetic excitations, and allows allows a reduction of the minimum characteristic length scale [1], with a corresponding increase of the attainable integration density. The use of nanostructuring of the surface provides additional possibilities for engineering the properties and various kinds of integrated optical components have been realized, such as Bragg gratings [2].

Photonic crystal as well as nanoplasmonic structures may be said to belong to the class of metamaterials, i.e., materials that gain their properties from their structure rather than directly from their composition. They are emerging as important technologies for modifying and engineering the passive properties of materials, e.g for application in optical signal processing and sensing. A further development in the field is the structuring of the electromagnetic properties to achieve a negative effective permittivity and negative effective permeability. These double negative or negative index materials, as they are denoted, allow achieving fundamentally different characteristics, that break with conventional wisdom, such as a perfect lens [3]. However, it is not yet clear how to structure the materials in order to achive double-negative characteristics at optical frequencies.

In order to generate or amplify light, active elements are needed and the only developed technology compatible with optoelectronic integration is based on III-V semiconductors. The possible choices of materials within group III and V is limited and the quasi-continuous nature of the electronic states in the conduction and valence band implies the equivalent of a material with a strong degree of inhomogeneous broadening. However, by exploiting quantization effects in structures with size on the order of the electron wavelength the energy level structure can be rendered discrete and the absolute values of the energy levels can be controlled. In this way the optical transition frequencies of the material can be modified. In semiconductors, 3-dimensional quantum confinement is realized by small protrusions, referred to as quantum dots, with a typical diameter of 10-20 nm and a height of a few nm, on top of a thin (wetting) layer. The low-dimensional quantum dot structures, depending on growth conditions, may also be in the form of truncated quantum wire structures, so-called quantum dashes [4]. Besides modifying the energy spectra, the quantum dots strongly alter the dynamics of the medium with important consequences for device properties.

By utilizing the the characteristics of quantum dots and photonic crystals to control both the energy levels and the dispersive properties, a number of new possibilities arise, e.g. within single-photon generation [5] as well as advanced nonliear switches [6].

In the talk we will mainly focus on the properties of quantum dots with respect to their application in lasers and amplifiers as well as examples of novel functionalities that they may enable.

It has been experimentally demonstrated that quantum dot SOAs enable very high saturation output power as well as operation over a broad range of wavelengths [7]. The saturation and noise properties of SOAs will be discussed based on a detailed theoretical model of the SOA [8]. The ultrafast dynamics of QD and quantum dash SOAs has been studied by pump-probe techniques [9,10] and is important in understanding the potential of QD SOAs for all-optical signal processing. In particular, reservoir effects associated with excited and wetting layer states of the SOA may profoundly influence the dynamics [11,12].

The discrete states of QD materials also open up the possibility of carrying out fundamental experiments sofar only performed in atomic gasses. For instance, electromagnetically Induced Transparency (EIT) was shown to enable a very spectacular slow-down of light in an ultracold atomic gas [13], but it is speculated that the same phenomenon could be observed in a QD waveguide [14]. If demonstrated experimentally this may pave the way for practical applications of slow-ligh effects, e.g. as microwave phase shifters. We will discuss the requirements to realize the regime of EIT in QD waveguides as well as alternative techniques [15,16] for controlling the speed of light.

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