Super-collimation of Electron Waves in Semiconductor Superlattices and the Paradigm of Transformation Electronics

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Abstract

The speed of integrated circuits is ultimately limited by the electron mobility, which depends on the effective mass of electrons in a semiconductor. Building on an analogy between electromagnetic media and semiconductors, we describe a new transport regime in a semiconductor superlattice characterized by extreme anisotropy of the effective mass and a minute inertia to movement – with zero effective mass – along a preferred direction of space, such that electron waves are super-collimated along that direction. We envision that this effect may pave the way for faster electronic devices and detectors, and new functional materials with a strong electrical response in the infrared regime.

1. Introduction

Metamaterials are composite metal-dielectric structures whose electromagnetic response is mainly determined by artificially built-in features and not directly by the chemical composition, and have received growing attention mainly since the beginning of this century [1]. The distinctive feature of metamaterials as compared to natural media is that their building blocks – the meta-atoms or inclusions – are macroscopic as compared to the atomic scale, but still sub-wavelength on the length scale determined by the electromagnetic radiation. This enables describing electromagnetic wave phenomena treating the metamaterial as a continuous medium, described by an effective permittivity and permeability in the simplest cases.

The metamaterial concept was initially developed under the framework of classical electromagnetism, but later it was extended to the elastic and acoustic cases. Moreover, in some sense, the metamaterial notion is not strange to the field of semiconductors, since semiconductor superlattices can be regarded as the counterpart of electromagnetic metamaterials but for electron waves. Superlattices were proposed by Esaki and Tsu more than forty years ago [2] based on the observation that if the characteristic length of a periodic structure is smaller than the typical mean free path distance of the electrons (some tens of nanometers), then the electronic band structure can depend on the composition of the lattice (e.g. the doping concentration or the composition of the alloy), rather than just on atomic properties. Thus, to some extent semiconductor superlattices may be seen as predecessors of electro-

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magnetic metamaterials. Based on the superlattice idea, Esaki and Tsu predicted the possibility of a negative differential conductance [2], and their pioneering work is the foundation of many spectacular advances in the semiconductor field [3], and enabled the design of photodetectors and photomultipliers with improved response, the demonstration of semiconductor lasers that emit in the mid- to far-infrared portion of the electromagnetic spectrum (the quantum cascade laser) [4], and the development of novel materials with ultra high electron and hole mobilities [5].

Until now, the obvious analogy between semiconductor superlattices and electromagnetic metamaterials received little attention, apart from isolated studies [6, 7]. The objective of this work is to bridge the two fields, and bring some of the ideas developed under the framework of electromagnetic materials to electronics. Inspired by the exciting paradigm offered by electromagnetic metamaterials and transformation optics [1], we develop the paradigm of “transformation electronics”, wherein the electron wave packets are constrained to move along desired paths. We envision that these ideas may enable tailoring the transport properties and the development of new ultrafast devices, as well as the design of new materials with enhanced electromagnetic response.

2. Superlattices with Extreme Anisotropy for the Effective Mass Tensor

In a semiconductor the effective mass determines the inertia of an electron to an external stimulus. In electronic circuits the electron flow is supposed to occur along a specific path, which determines a preferred direction of motion. We suggest to engineer the electron mass in such a way that (*I*) all the available electronic states contribute to the electron flow along the preferred direction of motion, and (*II*) the intrinsic electron resistance to movement is greatly reduced.

Clearly, a superlattice with the property (*I*) must be anisotropic. Indeed, in order that the velocity $\mathbf{v}_g = \hbar^{-1}\nabla_{\mathbf{k}}E$ is parallel to the desired direction of flow (let us say z) for an arbitrary electronic state, it is necessary that the energy dispersion $E = E(\mathbf{k})$ depends exclusively on the z- component of the wave vector, so that the effective mass tensor satisfies

$$m_{xx}^* = m_{yy}^* = \hbar^2\left(\partial^2 E/\partial k_x^2\right)^{-1} = \hbar^2\left(\partial^2 E/\partial k_y^2\right)^{-1} = \infty, \tag{1}$$

i.e. the resistance to a flow in the x-y plane must be extremely large. To satisfy the requirement (*II*) it is necessary that the component of the effective mass along z is near zero:

$$m_{zz}^* = \hbar^2\left(\partial^2 E/\partial k_z^2\right)^{-1} \approx 0. \tag{2}$$

Thus ideally we would like to have an infinite mass for directions parallel to the x-y plane, and a near-zero mass along the z-direction, and thus an effective mass tensor characterized by *extreme anisotropy*. How can one design an electronic material with such properties?

Notably, electromagnetic metamaterials and graphene superlattices with extreme anisotropy have recently received great attention due to their unusual potentials in guiding light and electrons with no diffraction [8-11]. Therefore, we suggest exploring some formal similarities between photonics and electronics to understand how a similar super-collimation effect and a near-zero mass can be obtained in semiconductor superlattices. In a recent work [12], we have argued that in certain conditions the propagation of electron waves in semiconductors with a zincblende structure is formally analogous to the propagation of light in a material characterized by a certain permittivity and permeability (Fig. 1). This analogy is consistent with what has been described in Ref. [6]. Thus, since metamaterials with extreme anisotropy can be realized by combining slabs of materials with complementary electromagnetic parameters [8, 9, 13], we expect that a superlattice with extreme anisotropy may be designed in the same manner.

At the conference, we will show how by pairing the binary compound HgTe with a ternary alloy of HdCdTe it may be possible to engineer the electronic structure in such a manner that the “low energy” physics and the transport properties are determined by a linear energy dispersion of the form $E \approx \hbar v_P |k_z|$, where v_P is a parameter with dimensions of velocity, which determines the effective velocity of the carriers along the z-direction. Graphene also has linear energy dispersion, but here we consider a bulk material. Moreover, we will prove that the electrical response of the superlattice may be extremely strong, particularly at low temperatures, and that the electrical conductivity may be characterized as well by extreme anisotropy. Our ideas may establish a new paradigm for an ultra-fast and extremely strong electronic response, which may be nearly independent of temperature in the limit of low temperatures, and exciting new developments in both electronics and photonics.

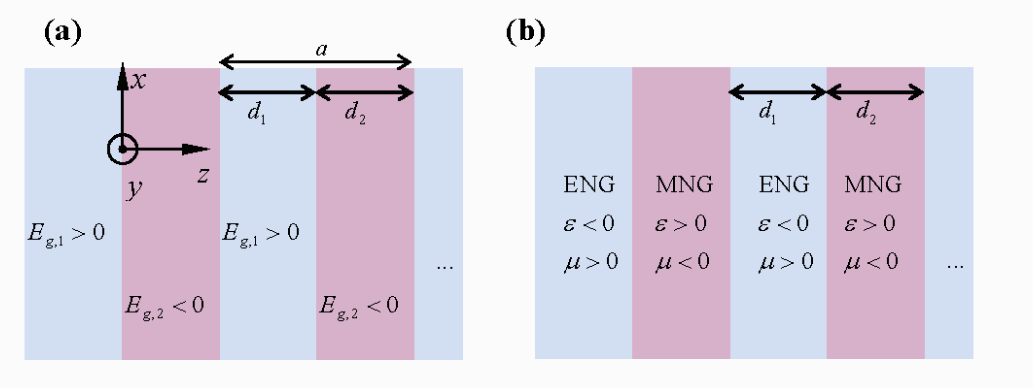

Fig. 1. [From [12]] Transformation Electronics: A stratified superlattice formed by pairing lattice-matched semiconductor materials with band gap energies with opposite signs (panel a) is in some sense the electronic dual of an electromagnetic metamaterial (panel b) formed by pairing slabs of ENG ($\varepsilon > 0$ and $\mu < 0$) and MNG ($\varepsilon < 0$ and $\mu > 0$) materials [6, 12]. It is known that the electromagnetic metamaterial of panel (b) can be characterized by an extremely anisotropic response, and hence we expect that a suitably designed superlattice will have similar properties but for electron waves (specifically $m^*_{xx} = m^*_{yy} = \infty$ and $m^*_{zz} \approx 0$).

References

[1] N. Engheta, R. W. Ziolkowski, Electromagnetic Metamaterials: Physics and Engineering Explorations, Wiley-IEEE Press, 2006.

[2] L. Esaki, R. Tsu, "Superlattice and Negative Differential Conductivity in Semiconductors", IBM Journal of Research and Development, 14, 61, 1970.

[3] F. Capasso, "Band-Gap Engineering: From Physics and Materials to New Semiconductor Devices", Science, 235, 172, 1987.

[4] J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, "Quantum Cascade Laser", Science, 264, 553, 1994.

[5] J. R. Meyer, et al, "Ultrahigh electron and hole mobilities in zero-gap Hg-based superlattices", Phys. Rev. B (RC), 38, 2204, 1988.

[6] L. Jelinek, J. D. Baena, J. Voves, and R. Marqués, "Metamaterial-inspired perfect tunneling in semiconductor heterostructures", New J. Phys. 13, 083011, 2011.

[7] V. V. Cheianov, V. Fal'ko, B. L. Altshuler, "The Focusing of Electron Flow and a Veselago Lens in Graphene p-n Junctions", Science 315, 1252, 2007.

[8] A. Salandrino, N. Engheta, "Far-field subdiffraction optical microscopy using metamaterial crystals: Theory and simulations", Phys. Rev. B, 74, 075103, 2006.

[9] Z. Jacob, L. V. Alekseyev, and E. Narimanov, "Optical Hyperlens: Far-field imaging beyond the diffraction limit", *Optics Express*, **14**, 8247, 2006.

[10] M. G. Silveirinha, P. A. Belov, C. R. Simovski "Ultimate limit of resolution of subwavelength imaging devices formed by metallic rods", Opt. Lett., 33, 1726, 2008.

[11] C.-H. Park, Y.-W. Son, L. Yang, M. L. Cohen, S. G. Louie, "Electron Beam Supercollimation in Graphene Superlattices" *Nano Lett.*, 8, 2920, 2008.

[12] M. G. Silveirinha, N. Engheta, "Transformation Electronics: Tailoring Electron's Effective Mass", (under review), 2012.

[13] S. A. Ramakrishna, J.B. Pendry, M.C.K. Wiltshire and W.J. Stewart, "Imaging the near-field", *J. Mod. Optics*, 50, 1419-1430, 2003.