Renormalized Landau quasiparticle dispersion revealed by photoluminescence spectra from a two-dimensional Fermi liquid at the MgZnO/ZnO heterointerface

V. V. Solovyev and I. V. Kukushkin
Institute of Solid State Physics, RAS, Chernogolovka 142432, Russia
(Received 11 April 2017; published 18 September 2017)

We analyze the low-temperature photoluminescence spectra from two-dimensional electron systems (2DESs) confined at $Mg_xZn_{1-x}O/ZnO$ heterojunctions as the electron density is decreased from 2.3×10^{12} to 3.5×10^{11} cm^{-2}. The value of the quasiparticle optical density-of-states mass is directly extracted from the width of the 2DES photoluminescence band and is shown to renormalize and double from the value close to that of bulk ZnO material, $0.3m_0$ (m_0 is the bare electron mass), to $0.6m_0$ due to electron-electron interactions as the interaction parameter r_s increases from 2.4 to 6.5. The experimentally probed quasiparticle energies far exceed the limits of Landau's Fermi-liquid theory.

DOI: 10.1103/PhysRevB.96.115131

The dynamics of correlated many-body quantum systems poses a great challenge for modern fundamental physics. As originally put forward by Landau half a century ago [1], the physical properties of an interacting Fermi system can in some cases be qualitatively similar to the physical properties of the gas of free fermions. Further quantitative correspondence can be established after introducing the idea of *quasiparticles* which emerge in Landau's theory of Fermi liquid (FL) and show the behavior of noninteracting fermions albeit possessing an interaction-altered or *renormalized* energy spectrum and the corresponding mass values.

Since its invention, Landau's FL theory has proved to be very successful in describing the thermodynamic properties of normal ^{3}He composed of neutral particles [2], degenerate semiconductors and normal metals [3] containing charged electronic Fermi systems, heavy nuclei composed of both neutrons and protons [4], and even such cosmological objects as neutron stars [5].

Based on the series expansion of the system total energy with respect to small deviations of the particle occupation numbers, the theory is inherently restricted to low excitation energies along with low temperatures. This knowledge is sufficient for determining, e.g., specific heat and other susceptibilities [1,6], and in principle it also allows for calculation of the quasiparticle band mass value. However, for large enough energies—approaching the characteristic Fermi energy or temperature scale—the theory goes wrong because quasiparticles are no longer well-defined objects because their decay rate (in other words, the imaginary part of the energy) increases significantly [6]. Therefore, a comprehensive experimental determination of physical parameters for FL systems is highly desirable.

Large excitation energies of Fermi systems, or quasiparticle energies, are not typically accessible in transport experiments or susceptibility measurements; however, they are naturally probed during investigation of a system's optical properties. For example, recent studies of conductivities at optical frequencies in Sr_2RuO_4 material [7] report FL behavior in the quasiparticle decay rate upon increasing their energy and system temperature. One more approach especially suitable for direct band-gap semiconductors stems from the use of valence-band states for creating excitations in the strongly correlated electronic FL system of the conduction band. With this technique, it has been demonstrated recently [8] that in the case of the two-dimensional FL realized in GaAs/AlGaAs quantum wells a rather strong renormalization of the electron mass (up to 35%) was detected for r_S values close to 4.5.

In this paper we show how direct interband transitions reveal even more prominent signatures of electron-electron interactions and the corresponding quasiparticle energy spectrum renormalization in the photoluminescence (PL) spectra of electron-doped MgZnO/ZnO heterointerfaces for record values of r_s up to 6.5. The developed straightforward analysis allows one to directly determine the full range of quasihole energies, extract the value of their optical density-of-states mass, and demonstrate its dependence on the FL interaction parameter $r_s = me^2/\epsilon\hbar^2\sqrt{\pi n}$ (here n is the 2D carrier density, m is the band electron mass, and ϵ is the medium dielectric constant).

Recently, high-quality $Mg_xZn_{1-x}O/ZnO$ heterojunctions (HJs) have emerged as an excellent test-bed for the study of electron-electron interaction effects in two dimensions. The extreme purity of the 2DES at these oxide interfaces is revealed by the outstanding values of electron mobilities exceeding 10^6 cm^2/V s [9,10] and demonstration of robust fractional quantum Hall effect states [11,12]. The large value of the bulk electron mass ($m = 0.3m_0$, m_0 being the bare electron mass) in a ZnO hosting material and its relatively small dielectric constant ($\epsilon = 8.5$) are both advantageous for enhancing the effect of interactions, compared, e.g., to AlGaAs/GaAs heterostructures. As a result, record values of the FL interaction parameter r_s up to 10 are readily achieved, and the interaction-induced effects were recently invoked for an explanation of the enhanced effective electron masses from transport and magnetoplasma resonance studies along with measured spin susceptibilities [13–17].

It has recently been shown that optical spectroscopy of interband transitions can be a valuable tool for probing the energy levels of the $Mg_xZn_{1-x}O/ZnO$ heterointerface confinement potential [18]. The object of the present paper is the PL band originating from the lowest electron subband occupied by electrons.

Our samples were grown on Zn-polar single-crystal ZnO substrates (Tokyo Denpa) by ozone-assisted molecular-beam epitaxy [19] with varying Mg mole fractions $x = 0.03$–0.19. Low-temperature ($T = 0.5$ K) transport measurements (not

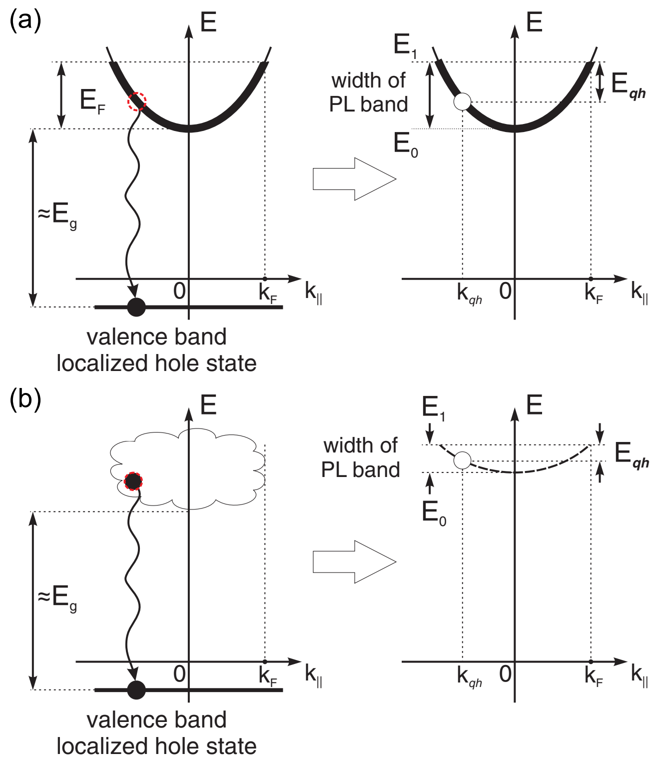

FIG. 1. Sketch of optical transitions present in a semiconductor 2DES and both its initial and final states in the case of (a) noninteracting and (b) interacting electrons. See text for details.

shown) provided the values of the corresponding electron density $n = 3.5 \times 10^{11}$–2.3×10^{12} cm^{-2} and mobility values $\mu > 100\,000$ cm^2/V s. Optically extracted electron densities (see Ref. [18] for details of the procedure) matched transport data well. Low-temperature ($T = 0.5$ K) PL measurements were carried out in a ^{3}He bath cryostat with magnetic fields up to $B = 15$ T normal to the 2DES plane. The samples were excited by the emission of a 325-nm He-Cd laser delivered by an optical fiber, and another fiber was used for PL signal collection. Optical spectra were dispersed by a single-stage spectrometer and detected with a liquid nitrogen-cooled CCD array; the final spectral resolution was 0.3 Å.

Before describing the experimental results, we first discuss some basic properties of electron-hole recombination in many-electron 2DESs. In the case of noninteracting electrons with a parabolic energy spectrum described by a mass value m, the system ground state is represented by all occupied single-particle quantum states inside a Fermi surface with all empty ones above it [see Fig. 1(a)]. The only system characteristics—the Fermi energy $E_F = n\frac{\pi\hbar^2}{m}$ and Fermi momentum $k_F = \sqrt{2\pi n}$—are solely determined by the electron density n. The low-intensity optical excitation creates the valence-band hole states located at some distance from the HJ while negligibly changing the 2DES electron density. These hole states are depicted in Fig. 1(a) by a single energy level corresponding to the situation of localized and therefore dispersion-free valence-band holes, which is relevant for our experiments as will become clear later. The recombination of an electron from the interior of a Fermi surface with the valence-band hole is indicated by a wavelike arrow. It results in emission of a photon possessing an energy close to the value of the semiconductor band gap E_g (which greatly exceeds all other relevant energies in the case of ZnO- and GaAs-based 2DESs) and the simultaneous creation of an empty state, or an elementary excitation called a *quasihole* inside the Fermi surface. The 2DES is left in an excited state the energy of which is fully described by the quasihole momentum k_{qh} and exactly coincides with the quasihole energy E_{qh} if counted downward from the level of Fermi energy. The corresponding spectral PL band results from all possible recombination processes occurring in the 2DES and its *energy span* is therefore determined by the allowed range of 2DES final state energies. As clearly seen from the sketches of Fig. 1(a), the width of the PL band is trivially equal to the 2DES Fermi energy, and this fact is well confirmed by numerous experimental data from the AlGaAs/GaAs heterostructures [20], where the interaction among electrons is relatively weak compared to the Fermi energy. Moreover, the quasihole energy dispersion turns out to be virtually equivalent to the electron dispersion, i.e., they have the same masses. It should also be outlined here that the localization of valence-band holes greatly simplifies the above analysis because both the details of their dispersion and the momentum conservation rule for optical recombination processes can be omitted in this case.

The situation is completely different if any present intra-2DES interactions are taken into account. Strictly speaking, this many-body problem has no unified theoretical description, neither for the 2DES ground state nor for its elementary excitations. In case the Fermi system remains "normal" (that is, not superconducting), some of its physical properties can be described by Landau's FL theory dealing with low-energy excitations only. Again, quasielectrons and quasiholes appear, but their energy dispersions and corresponding masses can differ drastically from those of the bare electron. Moreover, the physical meanings of both the electron mass and the Fermi energy are no longer valid in the interacting electron system [the cloudlet in the left part of Fig. 1(b) aims to illustrate this situation]. From the previous simple physical picture only the Fermi momentum k_F survives due to the Luttinger theorem [21].

Despite these complications, the same possibility of optical creation of the 2DES quasiholes that was described before remains. We take the opportunity to study the *spread* of the quasihole energy dispersion curve when its momentum changes from zero to k_F. By analogy with the noninteracting case, one can arrive at the conclusion that the width of the PL band again represents the allowed range of energies for the remaining 2DES quasiholes [Fig. 1(b)]. Even though it is not possible to extract from the energy spread the expression for the quasihole energy dispersion, the signatures of its renormalization may become apparent. To characterize this deviation most vividly, it is useful to introduce *a quasihole optical density-of-states mass* m_{qh} describing the parabolic dispersion the energy of which at the Fermi momentum k_F is equal to the change in the quasihole energy when its momentum varies from zero to k_F. As was shown before, for the case of noninteracting electrons with parabolic dispersion the quasihole optical

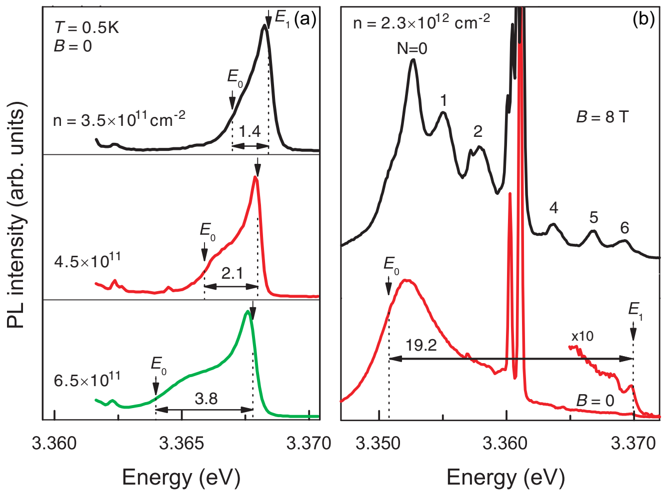

FIG. 2. (a) PL spectra from the $Mg_xZn_{1-x}O$/ZnO heterojunctions with the electron density $n = 3.5 \times 10^{11}$–6.5×10^{11} cm^{-2}. The energy width of the PL band originating from the lowest electron subband is indicated. (b) The PL spectra from the $Mg_xZn_{1-x}O$/ZnO HJ with the highest electron density studied, $n = 2.3 \times 10^{12}$ cm^{-2}, at magnetic fields $B = 0$ and 8 T. The splitting of a PL band into Landau levels is clearly visible. The Landau-level numbers are indicated.

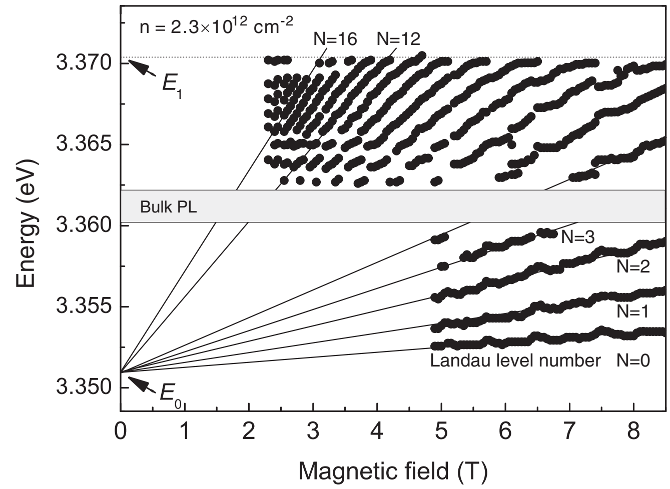

FIG. 3. Landau-level fan in PL spectra from the HJ sample with $n = 2.3 \times 10^{12}$ cm^{-2}. The zero-field continuation of LLs (highlighted by solid lines) points to a common origin coinciding with the E_0 energy. Each LL terminates at an energy corresponding to E_1 in a corresponding magnetic field.

density-of-states mass automatically coincides with the electron mass.

Figure 2(a) demonstrates the PL spectra from the $Mg_xZn_{1-x}O$/ZnO HJs with electron density $n = 3.5 \times 10^{11}$–6.5×10^{11} cm^{-2}. The dominating spectral lines at 3.357–3.362 eV are observed for all samples; they correspond to the donor-bound excitons in bulk ZnO material as documented in the literature [22]. For the low-density samples, the PL band at approximately 3.368 eV was earlier identified as originating from the filled lowest electron subband at the HJ [18]. The notations E_0 and E_1 indicate the low- and the high-energy sides of the PL band, respectively, the former being naturally more broadened due to the decreased quasiparticle lifetime with higher excitation energies. These energies would correspond in the case of the noninteracting 2DES to the optical annihilation of the electron from the bottom of the electron subband (at $k = 0$) and from the Fermi energy E_F, respectively. As already discussed, it is more appropriate to associate these events in interacting electron systems with the creation of the quasihole at $k = 0$ and at k_F. An increase in the electron density results in the expected widening of the PL band, its energy spread being indicated for each spectrum in Fig. 2 by an arrow and a magnitude (in meV).

For higher electron densities, the lower boundary of the PL band becomes blurred due both to the overlap with the bulk lines and because of the intrinsic PL line broadening [Fig. 2(b)]. In this case, we applied a perpendicular magnetic field and observed the splitting of the PL band into a characteristic Landau-level fan (see Fig. 3). The continuations of the Landau levels to a zero magnetic field point to their common origin coinciding with the E_0 energy. This approach also helps us ascertain the E_0 and E_1 positions for the highest-density sample, where the lower PL energy edge is significantly broadened due to the quasihole damping (equivalently, the imaginary part of its energy), and the PL intensity at E_1 is greatly reduced.

The PL spectra also reveal a very significant transformation of the spectral shape as the 2DES density increases: the peak in the intensity shifts from the higher-energy side at lower densities to the opposite side for the highest-density sample. This behavior is connected with the phenomenon of the Mahan exciton [23], which is also responsible for the unusual PL spectra transformation in the magnetic field for the lower-density samples where the PL Landau-level fan looks "inverted" (not shown); these details will be extensively discussed elsewhere. Despite this feature, the E_0 and E_1 positions are again confirmed by the PL spectra magnetic field dependencies.

The E_1-E_0 bandwidth of the 2DES recombination line in the PL spectra provides a direct measure of the quasihole dispersion extension. We associate it with the already introduced quasihole optical density-of-states mass through the expression $m_{qh} = n\frac{\pi\hbar^2}{E_1-E_0}$. Figure 4 demonstrates the dependence of the extracted value of this quantity on the 2DES density and also on the interaction parameter r_s. It is clearly seen that for the highest electron density the quasihole optical density-of-states mass approaches the bare electron band mass in ZnO. This is in accordance with the discussed case of the (nearly) noninteracting system. At the same time the dependence reveals a significant mass renormalization at low densities due to the increase of the interaction parameter r_s, and the mass even doubles for the sample with $n = 3.5 \times 10^{11}$ cm^{-2}.

The remaining question concerns the possible effect of the energy dispersion of the valence-band holes in case they are not localized as suggested earlier. It is rather obvious that due to the momentum conservation law, which holds during the optical recombination processes, the energy extension of the valence-band holes will contribute *additively* to the

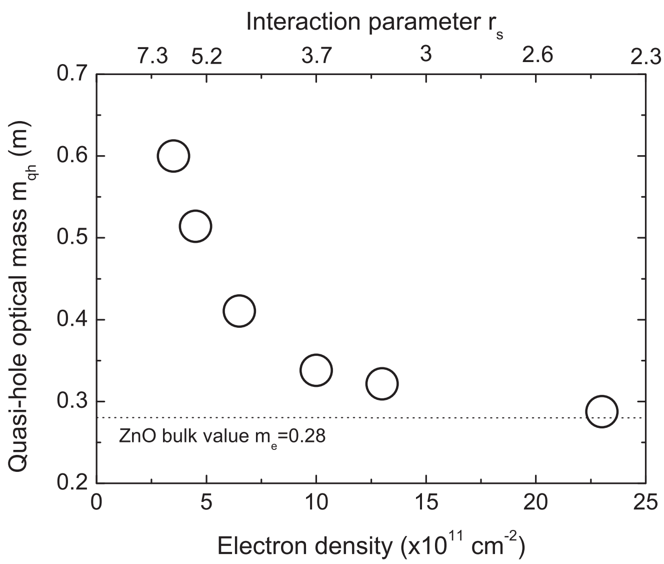

FIG. 4. Dependence of a quasihole optical density-of-states mass extracted from the PL bandwidth on the 2DES concentration and on the corresponding interaction parameter r_s. Strong renormalization from the bare bulk ZnO electron mass value $0.28m_0$ (dashed line) is observed for decreasing densities.

resulting PL bandwidth. This means that the PL band energy spread will correspond to the reduced mass of both the valence-band hole and the 2DES quasihole, which is always *less* than the mass of any of the constituents. As literature-reported values of the top valence-band hole mass are less than $0.6m_0$ (Ref. [24]), and the observed PL bandwidths would correspond the reduced mass of $>0.6m_0$ for the lowest-density sample, this precludes the assumption of the free motion of the valence holes. Unlike the above-mentioned AlGaAs/GaAs systems where the valence-band holes were localized by an artificially introduced layer of acceptors, their localization in MgZnO/ZnO systems is facilitated by natural defects, most probably residual acceptors.

In conclusion, we extracted from the PL spectra of strongly correlated 2DESs at $Mg_xZn_{1-x}O$/ZnO heterointerfaces the valuable quantitative properties of an interaction-renormalized energy spectrum of hole-type quasiparticles. The value of the quasiparticle optical density-of-states mass is shown to increase as the interaction parameter r_s increases from 2.4 to 6.5, doubling from the value of approximately $0.3m_0$, corresponding to the electron mass in bulk ZnO material, to $0.6m_0$. Our method experimentally probes the quasiparticle energies which far exceed the limits of Landau's FL theory and demonstrates the existence of well-defined quasiparticles in this previously unexplored regime.

We thank the Russian Scientific Foundation (Grant No. 14-12-00693) for financial support.

[1] L. D. Landau, Zh. Eksp. Teor. Fiz. **30**, 1058 (1956) [Sov. Phys. JETP **3**, 920 (1957)].
[2] G. Baym and C. Pethick, *Landau Fermi-Liquid Theory: Concepts and Applications* (Wiley, New York, 2004).
[3] D. Pines and P. Nozieres, *The Theory of Quantum Liquids* (Benjamin, New York, 1969).
[4] A. B. Migdal, *Theory of Finite Fermi Systems and Applications to Atomic Nuclei* (Wiley, New York, 1967).
[5] G. Baym and S. A. Chin, Nucl. Phys. A **262**, 527 (1976).
[6] E. M. Lifshitz and L. P. Pitaevskii, *Statistical Physics* (Butterworth-Heinemann, Oxford, 1999), Vol. 9, Part 2.
[7] D. Stricker, J. Mravlje, C. Berthod, R. Fittipaldi, A. Vecchione, A. Georges, and D. van der Marel, Phys. Rev. Lett. **113**, 087404 (2014).
[8] I. V. Kukushkin and S. Schmult, JETP Lett. **101**, 693 (2015).
[9] J. Falson, M. Uchida, J. H. Smet, T. H. Arima, A. Tsukazaki, and M. Kawasaki, Scientific Reports **6**, 26598 (2016).
[10] D. Maryenko, J. Falson, Y. Kozuka, A. Tsukazaki, M. Onoda, H. Aoki, and M. Kawasaki, Phys. Rev. Lett. **108**, 186803 (2012).
[11] A. Tsukazaki, A. Ohtomo, T. Kita, Y. Ohno, H. Ohno, and M. Kawasaki, Science **315**, 1388 (2007).
[12] A. Tsukazaki, S. Akasaka, K. Nakahara, Y. Ohno, H. Ohno, D. Maryenko, A. Ohtomo, and M. Kawasaki, Nat. Mater. **9**, 889 (2010).
[13] Y. Kasahara, Y. Oshima, J. Falson, Y. Kozuka, A. Tsukazaki, M. Kawasaki, and Y. Iwasa, Phys. Rev. Lett. **109**, 246401 (2012).
[14] D. F. Kärcher, A. V. Shchepetilnikov, Yu. A. Nefyodov, J. Falson, I. A. Dmitriev, Y. Kozuka, D. Maryenko, A. Tsukazaki, S. I. Dorozhkin, I. V. Kukushkin, M. Kawasaki, and J. H. Smet, Phys. Rev. B **93**, 041410(R) (2016).
[15] A. Tsukazaki, A. Ohtomo, M. Kawasaki, S. Akasaka, H. Yuji, K. Tamura, K. Nakahara, T. Tanabe, A. Kamisawa, T. Gokmen, J. Shabani, and M. Shayegan, Phys. Rev. B **78**, 233308 (2008).
[16] V. E. Kozlov, A. B. Van'kov, S. I. Gubarev, I. V. Kukushkin, V. V. Solovyev, J. Falson, D. Maryenko, Y. Kozuka, A. Tsukazaki, M. Kawasaki, and J. H. Smet, Phys. Rev. B **91**, 085304 (2015).
[17] J. Falson, Y. Kozuka, J. H. Smet, T. Arima, A. Tsukazaki, and M. Kawasaki, Appl. Phys. Lett. **107**, 082102 (2015).
[18] V. V. Solovyev, A. B. Van'kov, I. V. Kukushkin, J. Falson, D. Zhang, D. Maryenko, Y. Kozuka, A. Tsukazaki, J. H. Smet, and M. Kawasaki, Appl. Phys. Lett. **106**, 082102 (2015).
[19] J. Falson, D. Maryenko, Y. Kozuka, A. Tsukazaki, and M. Kawasaki, Appl. Phys. Express **4**, 091101 (2011).
[20] I. V. Kukushkin and V. B. Timofeev, Adv. Phys **45**, 147 (1996).
[21] A. B. Migdal, Zh. Eksp. Teor. Fiz. **32**, 399 (1957) [Sov. Phys. JETP **5**, 333 (1957)]; J. M. Luttinger, Phys. Rev. **119**, 1153 (1960).
[22] B. K. Meyer, J. Sann, S. Eisermann, S. Lautenschlaeger, M. R. Wagner, M. Kaiser, G. Callsen, J. S. Reparaz, and A. Hoffmann, Phys. Rev. B **82**, 115207 (2010).
[23] G. D. Mahan, Phys. Rev. **153**, 882 (1967); **163**, 612 (1967).
[24] H. Morkoc and U. Ozgur, *Zinc Oxide: Fundamentals, Materials and Device Technology* (Wiley, New York, 2009), Chap. 1 and references therein.