Program Book

Orbitronics: Current Status and Perspectives

일시: 2022. 10. 14 (금), 10:30~17:30

장소: KAIST KI빌딩 2층 매트릭스홀

후원: 한국자기학회 스핀트로닉스 분과

조직위원: 이현우 (포항공대), 이경진 (KAIST), 박병국 (KAIST)

* 참석을 원하시는 분은 9월 30일까지 최선영 선생님 (sun.0@kaist.ac.kr) 께 이름/소속을 이메일로 보내주시기 바랍니다.

* 학회장소 인원제한 (~ 70명)으로 인해 등록자가 많은 경우, zoom 온라인 전송을 동시에 진행할 수 있습니다. 현재는 off-line만 하는 것이 계획입니다.

* 한국자기학회의 지원으로 등록비 없습니다. 등록비가 없는 관계로 점심식사는 각자 KAIST 교내 식당에서 해결 부탁드립니다 (약 5천원)

한국자기학회
The Korean Magnetics Society

모시는 글

오비트로닉스는 그동안 간과되어 왔던 ‘고체 내에서의 오비탈 자유도가 비평형 물리현상에 어떤 영향을 미치는가’를 연구하는 분야입니다. 오비트로닉스 분야는 지금까지 국내 이론/실험 그룹들에 의해 선도되어 왔고, 최근 다양한 해외 연구그룹들이 후속 연구를 시작하면서 점차 이 분야에 대한 관심이 커져가고 있습니다.

그러나, 오비트로닉스 연구에 대한 회의(懷疑)도 여전히 존재하는 것이 사실입니다. 이러한 회의는 부분적으로 초기 연구가 스핀궤도결합에 의해 발생하는 다양한 스핀관련 현상을 오비탈 관점에서 재해석하는 수준에 머물렀던 것에 기인합니다. 어떤 분야이든 기존에 알려져 있던 현상의 ‘재해석’으로부터 시작하는 것은 어찌 보면 초기연구가 흔히 갖는 특성일 수 있으나, 이제는 오비탈 자유도에 의해 발생하는 새로운 현상들에 대한 연구가 필요한 시점입니다.

또한 오비트로닉스 연구에 대한 회의는 격자(lattice)에 의해 회전대칭이 깨져있는 고체 내에서 오비탈 각운동량(orbital angular momentum; OAM)의 이동을 제대로 기술/측정할 수 있는가 혹은 대부분의 OAM 이 격자로 빠져나가는 상황에서 OAM 이 ‘큰’ 새로운 효과를 만들 수 있는가와 같은 보다 근본적인 질문들과도 연관되어 있습니다. 이러한 질문들 중 일부는 오해에서 기인한 측면이 있지만, 다른 일부는 여전히 열려있는 질문입니다.

이번 워크숍이 오비트로닉스 연구의 현 상황과 함께, 새로운 연구방향과 전술한 질문들에 대해 논의하고 서로의 생각을 공유하는 자리가 되었으면 합니다. 이 모든 내용들이 워크숍을 통해 만족스럽게 해소되지는 않을 것으로 생각합니다만, 이현우 교수의 tutorial 강연과 초청연사들의 panel discussion 을 통해 좋은 출발점은 될 것으로 기대합니다.

끝으로 이번 워크숍을 후원해주신 한국자기학회에 감사드립니다.

- 조직위원 일동

발표 순서

10:30-11:30: 이현우 (포항공대)

'Orbital dynamics in nonmagnetic systems' (tutorial talk)

11:30-12:00: 김경환 (KIST)

'Hidden degrees of freedom of orbital angular momentum'

12:00-13:30: 점심

13:30-14:00: 박병국 (KAIST)

'Efficient conversion of orbital Hall current to spin current'

14:00-14:30: 최경민 (성균관대)

'Optical detection of orbital Hall effect and orbital Edelstein effect'

14:30-15:00: Coffee break

15:00-15:30: 김상훈 (울산대)

'Recent progress in development of new ferromagnetic systems for orbitronics'

15:30-16:00: 이경진 (KAIST)

'Orbital torque, orbital pumping, and chiral magnetoresistance'

16:00-16:30: Coffee break

16:30-17:30: Panel discussion: Quo Vadis Orbitronics?

(발제자: 이현우, Panelist: 초청연사, Moderator: 이경진)

Orbital dynamics in nonmagnetic systems

Hyun-Woo Lee

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This tutorial aims to deliver motivations to study orbital dynamics and illustrate its fundamental physics. Starting from the well-established intrinsic spin Hall effect, we argue that the orbital angular momentum of electrons is crucial for the intrinsic spin Hall effect in centrosymmetric systems. We then discuss the issue of orbital quenching. We demonstrate that the crystal field's suppression of the electron orbital angular momentum is limited to equilibrium, and the orbital angular momentum can easily develop in many materials when an external electric field is applied. We then review recent efforts to probe the orbital dynamics experimentally. The main ideas of the orbital torque and orbital accumulation will be briefly discussed. Formal aspects of the orbital dynamics will also be discussed, which imply important differences between the orbital and the spin dynamics.

Hidden Degrees of Freedom of Orbital Angular Momentum

Kyoung-Whan Kim

Center for Spintronics, Korea Institute of Science and Technology

After the recent re-examination of the orbital Hall effect [1], understanding the dynamics of orbital angular momentum has become important in the aspect of fundamental science and spintronic applications. Traditionally, it has been believed that the dynamics of orbital angular momentum and that of spin angular momentum are qualitatively similar, so it is difficult to separate those contributions experimentally. The distinction is challenging even theoretically, because their dynamics are rooted in the same commutator algebra.

In this work, we start from a fundamental algebraic difference between the orbital and spin angular momentum operators and show differences in their dynamics. Nontrivial anticommutators between the orbital angular momentum introduce hidden degrees of freedom which we call the orbital angular position and the orbital torsion [2]. The hidden degrees of freedom mediate the oscillation of the orbital angular momentum even without breaking time-reversal or spatial-inversion symmetry. Such an oscillation has no spin counterpart since the spin angular momentum does not oscillate unless at least one of the symmetries is broken. Our quantum Boltzmann approach indicates that considering the orbital angular position is essential for theoretical description of orbital transport. Also, we propose several experimental methods to measure the distinct dynamics of orbital angular momentum.

[1] D. Go, D. Jo, C. Kim, and H.-W. Lee, *Phys. Rev. Lett.* **121**, 086602 (2018).

[2] S. Han, H.-W. Lee, and K.-W. Kim, *Phys. Rev. Lett.* **128**, 176601 (2022).

Efficient conversion of orbital Hall current to spin current

Byong-Guk Park

Materials Science and Engineering, KAIST, Korea

Recent theory revealed that orbital Hall effect creates orbital current, which can be much larger than spin-Hall-induced spin current. However, orbital current cannot directly exert a torque on a ferromagnet, requiring a conversion process from orbital current to spin current. In this talk, we report two effective methods of the conversion through spin-orbit coupling engineering, which allows us to unambiguously demonstrate orbital-current-induced spin torque, or orbital Hall torque. We find that orbital Hall torque is greatly enhanced by introducing either a rare-earth ferromagnet Gd or a Pt interfacial layer with strong spin-orbit coupling in Cr/ferromagnet structures, indicating that the orbital current generated in Cr is efficiently converted into spin current in the Gd or Pt layer. Our results offer a pathway to utilize the orbital current to further enhance the magnetization switching efficiency in spin-orbit-torque-based spintronic devices.

[1] S. Lee, et al, Commun. Phys. 4, 234 (2021).

Optical detection of orbital Hall effect and orbital Edelstein effect

Gyung-Min Choi

Department of Energy Science, Sungkyunkwan University, Suwon, Korea

Recently, there has been a renewed interest for the orbital degree of freedom of electrons in non-magnetic materials. Theoretical works have predicted that an external charge current on non-magnetic materials can induce an orbital current in the bulk by orbital Hall effect[1-4] and an orbital magnetism at the interface by orbital Rashba-Edelstein effect[5-7]. However, the experimental detection of the orbital-driven effect is tricky because it has the same symmetry to the spin-driven effect, such as spin Hall effect and spin Rashba-Edelstein effect. Here we show our recent results of the magneto-optical Kerr rotation on the Ti bulk[8], the Cu/CuOx interface[9], and the MoS_2 monolayer and bilayer[10]. Since the Kerr rotation is much more sensitive on the orbital moment than on the spin moment in materials with weak spin-orbit coupling, we interpret our results in terms of the orbital-driven effect.

[1] B. A. Bernevig et al. *Phys. Rev. Lett.* **95**, 066601 (2005).

[2] H Kontani et al. *Phys. Rev. Lett.* **102**, 016601 (2009).

[3] T Tanaka et al. *Phys. Rev. B* **77**, 165117 (2008).

[4] D. Go et al. *Phys. Rev. Lett.* **121**, 086602 (2018).

[5] S. R. Park et al. *Phys. Rev. Lett.* **107**, 156803 (2011).

[6] D. Go et al. *Sci. Rep.* **7**, 46742 (2017).

[7] L. Salemi et al. *Nat. Commun.* **10**, 5381 (2019).

[8] Y.-G. Choi *et al.* submitted.

[9] K.-H. Ko *et al.* in preparation.

[10] W.-B. Lee *et al.* in preparation.

Recent progress in development of new ferromagnetic systems for orbitronics

Sanghoon Kim

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In the condensed matter physics, various types of current such as spin current and valley current as well as charge current have been discovered. Many of the newly discovered currents are of great interest for the industry as well as the physics community. The main reason is that they can be breakthrough for overcoming limitations of the existing memory and computing devices that operate based on the charge current. Recently, it has been theoretically proposed that orbital current can be generated, and it has been experimentally demonstrated in several metallic systems. Orbital current is expected to have higher conductivity than existing spin or valley currents particularly in 2D Van der Waals systems. This implies that material approach can offer a possibility to realize orbital-current-based devices prior to spin-based systems. In this presentation, I will introduce several material systems with exotic phenomena and discuss possibilities to find large orbital current in those systems.

Orbital torque, orbital pumping, and chiral magnetoresistance

Kyung-Jin Lee

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Spin-orbit torque (SOT), which is considered as a write scheme for next-generation MRAMs, arises from the charge-to-spin conversion via spin-orbit coupling (SOC). For efficient SOTs, it is of crucial importance to enhance the charge-to-spin conversion efficiency, which requires a detailed understanding of various SOC effects.

In this talk, we will describe the orbital torque [1] and the anomalous spin-orbit torque. The orbital torque in ferromagnet (FM)/normal metal (NM) bilayers arises from a combined action of three processes [2]: First, the orbital Hall current is generated in NM. Second, this orbital current is injected to FM and then is converted to a spin current via SOC of FM. Third, this spin current exerts a spin torque on the magnetization of FM. As the reciprocal process of orbital torque, the magnetization dynamics in the presence of SOC of FM pumps an orbital current to NM (i.e., orbital pumping) and this orbital current is converted to a transverse electric field (i.e., inverse orbital Hall effect). We will describe a numerical study on the orbital pumping and inverse orbital Hall effect in FM/NM bilayers. If time is allowed, we will also discuss the magnetoresistance of heterostructures containing a chiral crystal where the orbital texture is determined by the lattice chirality.

[1] D. Lee et al., "Orbital torque in magnetic bilayers", *Nat. Commun.* **12**, 6710 (2021).

[2] D. Go and H.-W. Lee, "Orbital torque: Torque generation by orbital current injection", *Phys. Rev. Research* **2**, 013177 (2020).