

Topological Phases in Condensed Matter

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Topological Phases in Condensed Matter

Summary

In this program, we have made tremendous progress in establishing synthesis capabilities in topological materials and heterostructures at NRL, optimizing and elucidating its properties, and demonstrating its advantages in potential practical device applications. Specifically, we have:

- Modeled current-generated spin polarization in topological insulators, which offered a resolution of the ongoing controversy regarding opposite signs of spin signal reported in the literature, and further highlight the importance of accounting for real experimental parameters such as spin dependent interface resistances.
- Established synthesis of high quality topological insulator (TI) and heterostructures by molecular beam epitaxy, particularly achieving bulk-insulating Bi_2Se_3 with an order magnitude enhancement in mobility and reduction in carrier concentration, which are instrumental in reduction in power consumption in spin-orbit torque switching of ferromagnets. Further developed the MBE growth of Bi_2Te_3 , a TI with out-of-plane polarization.
- We have developed In_2Se_3 as single crystalline spin-sensitive tunnel barrier for Bi_2Se_3 , it helps preserve the spin texture of the Bi_2Se_3 at the interface, and serve as an insulating layer to prevent current shunting through the ferromagnet (important for power reduction).
- We have developed the growth of Bi_2Se_3 on a magnetic insulator YIG (in collaboration with AFRL), and characterized spin transport across the interface, which enabled us to determine intrinsic parameters such as charge-to-spin conversion efficiency and spin Hall angle of the Bi_2Se_3 .
- We have achieved highly efficient spin-orbit torque Switching in $\text{Bi}_2\text{Se}_3/\text{Fe}_3\text{GeTe}_2$ van der Waals heterostructures with low critical current density, attributed to weak interlayer interaction at the interface that preserves the singly degenerate spin polarization. Our results highlight the clear advantage of all-vdW heterostructures, an important step towards realizing next generation low-power non-volatile memory and spintronic devices.

Technical Objective

The principle objective of this new start is to develop a fundamental understanding of topologically protected states which occur in a variety of materials - topological insulators, Dirac and Weyl semimetals -- and to demonstrate topologically protected charge and spin transport in these emergent quantum materials for future DoD applications in quantum information processing and high speed electronics and spintronics.

Technical Approach

The technical approach will be based upon demonstrated strengths and collaborative interactions between the participants in Code 6300. The effort will capitalize on NRL's leadership and expertise in semiconductor/metal heterostructures synthesis, spin injection / transport in semiconductors, as well as our unique expertise in detect, control, and manipulate current generated spins in the topological insulator systems using ferromagnet/tunnel barrier contacts and utilizing magneto optical Kerr effect.

Specifically, we will synthesize topological insulators such as Bi₂Se₃, Sb₂Te₃, and Bi₂Te₃ by molecular beam epitaxy (MBE), and optimize materials properties through doping, alloying, and heterostructuring, which would further allow us to explore novel interface effects. Leveraging our extensive expertise on the direct electrical access to the TI spin system, we will also fabricate prototype devices to utilize these spins to switch the magnetization of an adjacent ferromagnet via spin orbit torque, a key operation in memory devices. Furthermore, based on our first demonstration that spin generated on a current-carrying TI can rotate the linear polarization of light, we will optimize material properties and detection geometries towards developing magnetic field-free magneto optical devices such as optical modulators and isolators.

For the topological semimetals, their epitaxial growth is still in the early stages, where most studies are done on bulk crystals, and thin film (necessary for practical device fabrications) growth has yet to be realized for materials such as TaAs, NbAs, TaP, Ta₃S₂, and Mo_{1-x}W_xTe₂. To overcome the challenge of low vapor pressure of the metals, we will explore both electron beam sources for MBE growth at the Epicenter, as well as metalorganic sources for chemical vapor deposition (MOCVD), where code 6300 will be receiving a MOCVD growth apparatus in July 2017 which will be available for this program.

The Hallmark properties we aim to demonstrate for the topological semimetals include quantum oscillations, where surface electron occupying a state on the Fermi arcs "zipping" back and forth across the bulk of the sample produces periodic oscillations as a function of the out-of-plane magnetic field; and chiral anomaly, which gives rise to a negative magnetoresistance, as well as a dissipationless axial current due to the valley imbalance in the occupation numbers of the two Weyl nodes. When a local magnetic field is applied along the injected current direction, this manifest as a spontaneous voltage/current without an applied electric field. Furthermore, leveraging our expertise in the electrical and optical (by MOKE) detection of spin-momentum locking in topological insulator surface states, we will apply similar methods to investigate spin transport in the Fermi arc states in Weyl semimetals.

The exotic physical properties of topological materials present a unique opportunity to understand the fundamental physical interactions and assist synthesis of these materials; to develop prototype devices to test the predicted exotic transport phenomena arising from their topological electronic states; and to develop charge and spin-based device functionality for future DoD applications.

Technical Progress

1. Modeling current-generated spin polarization in topological insulators

One of its most striking properties of topological materials such as topological insulators (TIs) is that of *spin-momentum locking* -- the spin of the TI surface state lies in-plane, and is locked at

right angle to the carrier momentum. An unpolarized charge current should thus create a net spin polarization whose amplitude and orientation are controlled by the charge current. As part of our earlier 6.1 efforts (WU#'s 4992, 1B81), we have pioneered the first spin potentiometric measurement to *electrically* detect spin polarization arising from spin-momentum locking in TI surface states using ferromagnet/tunnel barrier contacts [Nature Nanotechnology **9**, 218 (2014)]. This method has since been widely adopted in the scientific communities to measure the current generated spin in other TI systems. However seemingly conflicting signs of the measured spin voltage have been reported, calling into question if topological surface states or trivial states such two-dimensional electron gas are being probed (which exhibit opposite signs of current-generated spin polarization).

To resolve this controversy, we have delved into the original model based on spin-dependent electrochemical potential that have been utilized to derive the expected sign of the current generated spin for TI surface states. We have in turn found fundamental flaws in this overly simplified model. Specifically, the TI was modeled as an isolated system, while any practical system will have electrical contacts for experimental access. These models neglect critical experimental parameters such as interface resistances, which can critically affect the sign of the spin signal measured.

Here we developed a Mott two-spin current resistor model which takes into account real experimental parameters such as spin-dependent resistances at the current injecting interface and in the TI channel, and show that such inclusion can lead to a crossing of the voltage potential profiles for the spin-up and spin-down electrons within the TI channel, which can lead to measured spin voltages of either sign. These findings offer a resolution of the ongoing controversy regarding opposite signs of spin signal reported in the literature, and further highlight the intricate nature of the seemingly straightforward electrical measurement of current generated spin in TI surface states, where real experimental parameters such as spin dependent resistances in both the channel and at current injecting interfaces must be considered to accurately account for the sign of spin voltage measured.

Title: Electrical detection of current generated spin in topological insulator surface states: Role of interface resistance

Authors: C. H. Li, O. M. J. van 't Erve, S. Rajput, L. Li, and B.T. Jonker

Type of Publication: Refereed journal

Where it Appeared: ", *Scientific Reports* **9**, 6906 (2019).

Publication Date: May 2019

Title: Reply to: "On the understanding of current-induced spin polarization of three-dimensional topological insulators"

Authors: C. H. Li, O. M. J. van 't Erve, S. Rajput, L. Li, and B.T. Jonker

Type of Publication: Refereed journal

Where it Appeared: ", *Nature Communications*, **10**, 2523 (2019).

Publication Date: June 2019

2. Developed synthesis of high quality topological insulator (TI) and heterostructures by MBE

During this project we have established the synthesis capability of high quality topological insulators such as Bi₂Se₃ by molecular beam epitaxy (MBE) at NRL.

Achieving bulk-insulating topological insulator (TI) Bi_2Se_3 by MBE.

Even though topological insulators should ideally exhibit an *insulating* bulk, i.e., the Fermi level should lay within the bulk bandgap, TIs such as Bi_2Se_3 are typically degenerately n-type doped, where the Fermi level is well within the conduction band, due to its very small bulk bandgap ($\sim 0.3\text{eV}$) and Se vacancy that's often present for MBE-grown thin films. Hence the bulk can be quite conductive, and significantly shuts current from the topological surface states where the spins are generated from spin-momentum locking, and non-ideal for minimizing power consumption. To this end we have worked to develop bulk insulating Bi_2Se_3 , through the approach of utilizing novel buffer layers such as $(\text{BiIn})_2\text{Se}_3/\text{In}_2\text{Se}_3$, where the Bi_2Se_3 film is isolated from the sapphire substrate, and hence minimizing the effects from defects at the substrate interface.

Through step-by-step efforts of optimizing the growth of In_2Se_3 thin films (with Bi_2Se_3 seed layer), and $(\text{BiIn})_2\text{Se}_3$ (In concentration $\sim 50\%$) buffer layer, we have now achieved a reduction in carrier concentration by more than an order of magnitude, well within the bulk insulating regime. A corresponding enhancement in carrier mobility by more than an order magnitude is also observed, to $\sim 10,000\text{ cm}^2/\text{Vs}$ at 2K, a level where quantum anomalous Hall effect can be observed. Furthermore, the temperature dependence of the resistivity and carrier concentration shows a metallic behavior, indicate that the electrical transport is dominated by the metallic surface state, rather than a semiconducting behavior that's often shown in literature (indicating that transport is still dominated by the semiconducting bulk states, except at low temperatures where surface states dominate upon bulk carrier freeze out).

This is a significant achievement and an important step towards minimizing power consumption in spin-orbit torque switching in TI/ferromagnet heterostructures.

In addition, we have also developed and optimized growth capabilities on 2" wafers. These materials are instrumental in supporting the 6.2 ARAP project on "Topologically Enabled Devices (TEDs)", during which we also provided samples for collaborators at AFRL (Dr. Arnold Keifer).

Developing the MBE growth of Bi_2Te_3 , a topological insulator with out-of-plane polarization.

One of the most intriguing properties of TIs is of spin-momentum locking, where the spins of the topological surface states are locked to the electron momentum. Hence an unpolarized current generates a spontaneous spin polarization, and in the case of the prototypical TI Bi_2Se_3 , an in-plane polarization. Such current-generated spin has been shown to switch the magnetization of an adjacent ferromagnet with in-plane magnetization such as NiFe. However, for another TI Bi_2Te_3 , the induced spins are not entirely in-plane, but rather has a significant out-of-plane component. This out-of-plane spin can be utilized to switch ferromagnets with out-of-plane magnetization, e.g., CoFeB, without an assist field. These perpendicular anisotropy FM provide the advantage of higher magnetic stability at smaller sizes (important for device down scaling), and faster switching speed (due to different switching dynamics).

To this end we have developed the MBE growth of Bi_2Te_3 thin films. Raman measurements show vibrational modes expected for Bi_2Te_3 , confirming the desired phase synthesized. ARPES measurements, done in collaboration with Prof. Lian Li at West Virginia University, verified its

expected band structure, including a warped Fermi surface that typically accompany significant out-of-plane spin component. In addition, we have further explored using similar $(\text{BiIn})_2\text{Se}_3/\text{In}_2\text{Se}_3$ buffer layers that we developed for the growth of high quality bulk-insulating Bi_2Se_3 for the growth of Bi_2Te_3 , and found that it helps improve the surface morphology, as well as reduced carrier concentration and enhanced mobility by a factor of 5. Research are underway to explore the field-free spin-orbit torque switching of out-of-plane ferromagnets with current-current generated spin from Bi_2Te_3 .

3. In_2Se_3 as single crystalline spin-sensitive tunnel barrier for Bi_2Se_3

Current-generated spin arising from spin-momentum locking in topological insulator (TI) surface states has been shown to switch the magnetization of an adjacent ferromagnet (FM) via spin-orbit torque (SOT) with much higher efficiency than heavy metals. However, in such FM/TI heterostructures, most of the current is shunted through the FM metal due to its lower resistance, and recent calculations have also shown that topological surface states can be significantly impacted when interfaced with a FM metal such as Ni and Co. Hence placing an insulating layer between the TI and FM will not only prevent current shunting, therefore minimizing overall power consumption, but may also help preserve the topological surface states at the interface.

To this end, semiconducting In_2Se_3 is isostructural and nearly lattice matched to Bi_2Se_3 (3.4% mismatch), making it a compelling candidate. We have carried out density functional theory (DFT) calculations, which show a type-I band alignment that would enable In_2Se_3 to be used as an insulating barrier, and that the linearly dispersing topological surface states of the Bi_2Se_3 and spin momentum locking is indeed preserved at the interface with the *beta* phase of In_2Se_3 .

We further developed the van der Waals epitaxial growth of *beta*-phase In_2Se_3 on Bi_2Se_3 by molecular beam epitaxy, where the RHEED pattern stays streaky during the heterostructure growth, indicating its single crystalline nature. This is further confirmed by atomic force microscopy image that shows that the triangular islands of the In_2Se_3 are aligned, i.e., coherently registered with the Bi_2Se_3 . Raman spectroscopy confirms that the In_2Se_3 is *beta* phase.

Through transport measurement we determine the dominant transport mechanism is tunneling, and further demonstrate its spin-sensitivity by the electrical detection of current-generated spin in Bi_2Se_3 surface states using an $\text{Fe}/\text{In}_2\text{Se}_3$ detector contact. Importantly, no anisotropic magnetoresistance (AMR) of the Fe is observed, indicating that no current flows through the Fe, i.e., the In_2Se_3 is indeed electrically insulating and preventing current shunting through the Fe.

This demonstration of an epitaxial electrically insulating crystalline barrier that can be grown directly on Bi_2Se_3 , verification that it preserves the topological surface state, and is spin sensitive, is an important step towards minimizing current shunting and overall power consumption in spin-orbit torque switching in TI/FM heterostructures in fully epitaxial topological spintronic devices.

Title: Spin-sensitive epitaxial In_2Se_3 tunnel barrier in $\text{In}_2\text{Se}_3/\text{Bi}_2\text{Se}_3$ topological Van der Waals heterostructure

Authors: C. H. Li, J. Moon, O. M. J. van 't Erve, D. Wickramaratne, E. Cobas, M. Johannes, and B. T. Jonker

Type of Publication: Refereed journal

Where it Appeared: *ACS Applied Materials & Interfaces* **14**, 34093-34100 (2022).

Publication Date: July 2022

4. Growth and spin transport across TI/FM interface

We have developed the growth of Bi₂Se₃ on YIG (Yttrium-Iron Garnet) thin films provided by our collaborator at AFRL (Dr. Mike Page), using a two-step growth method. YIG exhibits very low damping and is an insulator, therefore facilitating effective characterization by techniques such as ferromagnetic resonance (FMR) (low damping) and magneto transport (no current shunting) measurements, to investigate spin transport across interfaces and determinate important intrinsic parameters such as charge-to-spin conversion efficiency and spin Hall angle of the Bi₂Se₃.

Characterizing spin transport across Bi₂Se₃/YIG interface.

We have carried out a comprehensive study of the interplay between spin currents in the TI and magnetization of the ferromagnet in these Bi₂Se₃/YIG thin films, using FMR and detailed angle-dependent magnetoresistance (ADMR) measurements. Our FMR measurements exhibit broadening of the FMR linewidth because of spin pumping from YIG to Bi₂Se₃, with an extracted effective spin-mixing conductance of $5 \times 10^{13} / \text{ohm-m}^2$. At the FMR frequency, a static voltage is observed in Bi₂Se₃ in a direction perpendicular to the applied magnetic field, providing evidence for the conversion of spin current into emf in the TI.

Systematic ADMR measurements in all three planes of the Bi₂Se₃-YIG bilayer structure and a Bi₂Se₃ reference film indicate that, in direct contrast to the negligible intrinsic ADMR typically observed in heavy metals, the intrinsic ADMR of Bi₂Se₃ itself must be considered to extract the MR associated with the charge-to-spin interconversion. Moreover, ruling out contribution from proximity-induced magnetism in the Bi₂Se₃ due to absence of AHE, we determine that the MR ratio associated with the interfacial interaction between the YIG and the Bi₂Se₃ is $\sim 0.04\%$ at 20 K. Based on these results, we further estimate an effective spin Hall angle of $\sim 0.1-0.4$ for Bi₂Se₃.

Title: Interplay of spin current and magnetization in a topological insulator/magnetic-insulator bilayer structure

Authors: X. Zhang, C. H. Li, J. Moon, S. Leontsev, M. R. Page, B. T. Jonker, and O. M. J. van 't Erve

Type of Publication: Refereed journal

Where it Appeared: *Phys. Rev. Materials* **6**, 074203 (2022).

Publication Date: July 2022

Improving interfacial quality of Bi₂Se₃/YIG heterostructure.

We have now further developed a new growth method, where a 2 nm amorphous Se buffer is first deposited at room temperature, followed by 1 nm Bi₂Se₃. This amorphous seed layer is then annealed at the growth temperature (290 °C) where it turns crystalline, as evident from the RHEED pattern evolving from a diffused background (indicating amorphous) into a streaky

pattern (crystalline and smooth). This ensures that the first layer of the Bi₂Se₃ right at the Bi₂Se₃/YIG interface is of high quality. The rest of the thin film is then grown on this crystalline 1 nm seed layer. Our preliminary ferromagnetic resonance measurements show that the damping across the Bi₂Se₃/YIG interface is significantly enhanced for films grown using this low-temperature amorphous Se buffer technique, indicating more efficient spin transport across the interface. Similar ADMR magneto transport measurements including ADMR are underway to characterize spin transport across this improved TI/FM interface.

5. Highly Efficient Spin-Orbit Torque Switching in Bi₂Se₃/Fe₃GeTe₂ van der Waals Heterostructures

Topological insulators (TIs) have shown promise as a spin-generating layer to switch the magnetization state of ferromagnets via spin-orbit torque (SOT) due to efficient charge-to-spin conversion efficiency of the TI surface states that arises from spin-momentum locking. However, when TIs are interfaced with conventional bulk ferromagnetic metals, the combination of charge transfer and hybridization can potentially destroy the spin texture and hampers the possibility of accessing the TI surface states.

Here we fabricate an all van der Waals (vdW) heterostructure consisting of molecular beam epitaxy grown bulk-insulating Bi₂Se₃ and exfoliated 2D metallic ferromagnet Fe₃GeTe₂ (FGT) with perpendicular anisotropy. By detecting the magnetization state of the FGT via anomalous Hall effect and magneto-optical Kerr effect measurements, we determine the critical switching current density for magnetization switching to be $J_c \approx 1.2 \times 10^6 \frac{A}{cm^2}$, the lowest reported for the switching of a perpendicular anisotropy ferromagnet using Bi₂Se₃. From second harmonic Hall measurements, we further determine the SOT efficiency to be in the range of $\xi_{DL} = 1.8 \pm 0.3$ and 1.4 ± 0.08 between 5 and 150 K, comparable to the highest values reported for Bi₂Se₃.

Our density functional theory calculations find that the weak interlayer interactions at the Bi₂Se₃/FGT interface lead to a weakened dipole at the interface, and suppress proximity induced magnetic moment on Bi₂Se₃. This enables direct access to the TI surface states contributed by the 1st quintuple layer, where the spins are singly degenerate with significant net in-plane spin polarization.

Our results highlight the clear advantage of all-vdW heterostructures with weak interlayer interactions that can enhance SOT efficiency and minimize critical current density, an important step towards realizing next generation low-power non-volatile memory and spintronic devices.

Title: Highly Efficient Spin-Orbit Torque Switching in Bi₂Se₃/Fe₃GeTe₂ van der Waals Heterostructures

Authors: Z M. Lohmann, D. Wickramaratne, J. Moon, M. Noyan, H.-J. Chuang, B. T. Jonker, C. H. Li

Type of Publication: Refereed journal

Where it Appeared: *ACS Nano*, in press. doi.org/10.1021/acsnano.3c09041

Publication Date: December 2023

Publication / patents

1. C. H. Li, O. M. J. van 't Erve, S. Rajput, L. Li, and B.T. Jonker, "Reply to: "On the understanding of current-induced spin polarization of three-dimensional topological insulators", *Nature Communications*, **10**, 2523 (2019).

2. C. H. Li, O. M. J. van 't Erve, C., Yan, L. Li, and B. T. Jonker, "Electrical detection of current generated spin in topological insulator surface states: Role of interface resistance", *Sci. Rep.*, **9**, 6906 (2019).
3. C. H. Li, O. M. J. van 't Erve, J. T. Robinson, Y. Liu, L. Li, and B.T. Jonker, "Direct Electrical Detection of Spin-Momentum Locking in Topological Insulator Bi_2Se_3 ," Invention disclosure, Navy Case # 103190. Patent # US 10,132,880 B2 issued Nov. 20, 2018.
4. C. H. Li, R. Goswami, G. G. Jernigan, C. S. Hellberg, and B.T. Jonker, "Solid phase epitaxy of 3C-SiC on Si(001)", Invention disclosure, Navy Case #103185-US3. Patent issued 6/16/2020.
5. O. M. J. van 't Erve, A. T. Hanbicki, K. M. McCreary, C. H. Li, and B. T. Jonker, "Optical Modulator Using the Spin Hall Effect in Metals"; Invention disclosure, Navy Case 103594-US3, Patent issued 5/26/2020.
6. C. H. Li, O. M. J. van 't Erve, J. T. Robinson, Y. Liu, L. Li, and B.T. Jonker, "Direct Electrical Detection of Current-Induced Spin Polarization Due to Spin-Momentum Locking in Topological Insulators", Navy Case # 107270-US2. Patent issued 12/1/2020.
7. C. H. Li, J. Moon, O. M. J. van 't Erve, D. Wickramaratne, E. Cobas, M. Johannes, and B. T. Jonker, "Spin-sensitive epitaxial In_2Se_3 tunnel barrier in $\text{In}_2\text{Se}_3/\text{Bi}_2\text{Se}_3$ topological Van der Waals heterostructure"; *ACS Applied Materials & Interfaces* **14**, 34093-34100 (2022). DOI: 10.1021/acsami.2c08053
8. X. Zhang, C. H. Li, J. Moon, S. Leontsev, M. R. Page, B. T. Jonker, and O. M. J. van 't Erve; "Interplay of spin current and magnetization in a topological insulator/magnetic-insulator bilayer structure," *Phys. Rev. Materials* **6**, 074203 (2022). DOI: 10.1103/PhysRevMaterials.6.074203;
9. C. H. Li, O. M. J. van 't Erve, J. T. Robinson, Y. Liu, L. Li, and B.T. Jonker, "Direct Electrical Detection of Current-Induced Spin Polarization Due to Spin-Momentum Locking in Topological Insulators", Navy Case #103190-US4. Patent issued 3/22/2022.
10. M. Lohmann, D. Wickramaratne, J. Moon, M. Noyan, H.-J. Chuang, B. T. Jonker, C. H. Li "Highly Efficient Spin-Orbit Torque Switching in $\text{Bi}_2\text{Se}_3/\text{Fe}_3\text{GeTe}_2$ van der Waals Heterostructures", *ACS Nano*, **18**, 680 (2024).

Recognition / Invited talks:

1. C. H. Li, "Direct electrical detection of spin-to-charge and charge-to-spin conversion in topological insulator surface states", Condensed Matter Seminar, Physics Department, University of Delaware, October 23, 2018.
2. C. H. Li, "Direct electrical detection of spin-to-charge and charge-to-spin conversion in TI surface states and Rashba 2DEG states", SPIE Optics + Photonics Conference, San Diego, CA, August 19-23, 2018.
3. C. H. Li, "Direct electrical detection of spin-momentum locking in topological insulators", Physics and Astronomy and Nanoscale & Quantum Phenomena Institute Colloquium, Ohio University, October 18, 2019. STRN: NRL/JA/7390/18/193
4. C. H. Li, "Direct electrical detection of spin-momentum locking in topological insulators", 2nd Workshop on Spins, Valleys, and Topological States in 2D and Layered Materials, San Sebastian, Spain, July 22-24, 2020. (Conference postponed due to COVID-19.) STRN: NRL/JA/7390/18/193

5. C. H. Li, "Direct electrical detection of spin-momentum locking in topological insulators", Physics Colloquium, Colorado State University, March 29, 2021. STRN: NRL/JA/7390/18/193
6. C. H. Li, "Direct electrical detection of spin-momentum locking in topological insulators", 2nd Workshop on Spins, Valleys, and Topological States in 2D and Layered Materials, San Sebastian, Spain, July 26-29, 2021. (Conference postponed due to COVID-19.) STRN: NRL/JA/7390/18/193
7. C. H. Li, Spin-momentum locking and spin-orbit torque switching in topological insulator heterostructures, Univ. of Denver, Jan. 26, 2022
8. M. Noyan, Spin-orbit torque switching of ferromagnet from bulk insulating Bi_2Se_3 in topological insulator/ferromagnet heterostructures, SPIE Optics and Photonics 2022, Aug. 21, 2022

Transitions to external programs:

6.2 external OSD ARAP program "Topologically Enabled Devices"

6.2 program "Low power, Ultrafast, Embeddable, Antiferromagnetic Memory"