Jacob Christensen, MSE 498, 6/30/2023

Outline for Paper on Antiferromagnetic Devices

- Intended audience is new scientists in the field of magnetics/electronics. Requires previous knowledge of magnetic phenomena.
- Main Idea: Antiferromagnetic materials for spintronics is a rising area for data storage and transfer which may provide advantages for both efficiency and scaling over ferromagnetic materials and other traditional electronic devices. Despite having challenges regarding practical implementations and exploitation, the potential of antiferromagnetic materials warrants the increasing attention within research and development.

- **Introduction**
    - The demand for higher density and faster data storage pushes scientists to look for ways to overcome barriers to Moore's law. This is crucial for our advancement in technological capabilities in the information age. Traditionally, we have used transistors which act as electrical signal logic gates, focusing on the transport of electrical charge. We may be able to turn to manipulating the quantum spin states of carriers instead, known as Spintronics.
    - Antiferromagnetic materials, in contrast to ferromagnetic materials, have an alternating spin order which results in a net zero magnetization. This property is crucial to the use of antiferromagnets within small devices.

The following may be included in introduction, or separate if it feels appropriate

- Antiferromagnets have been proven to have worth over the last few decades
    - **They have been used in applications for magnetic memory devices**. An antiferromagnetic layer can be used to pin a ferromagnetic layer, allowing a second ferromagnetic layer to freely switch. This gives two different states with different resistances read out by a current.
        - The antiferromagnet is highly resistant to outside fields, so the ferromagnetic pinned layer won't be switched by unintentionally reordering the antiferromagnet.
        - **HDD and MRAM:** HDD memory disks have widely used antiferromagnets for this purpose. They have a single spin valve setup in a read head which moves over a disk with magnetic domains acting as the memory bits. MRAM, a budding technology, also uses antiferromagnets in the magnetic tunnel junction cells that act as the memory bits for the device.

    - But antiferromagnets may be useful beyond pairing with ferromagnetic materials. **They are resilient to outside fields, they do not produce large stray fields, and they have very fast switching dynamics**. (https://doi.org/10.1016/j.fmre.2022.03.016)

<u>Begin in depth discussion of features which make antiferromagnets interesting</u>

- Antiferromagnets can surpass ferromagnetic materials in speed due to faster switching dynamics
    - Antiferromagnetic materials have higher resonant frequencies than ferromagnetic materials.
    - The spins in an antiferromagnetic material have a strong exchange interaction (quantum mechanical concept) which causes spins to precess very quickly. (doi: 10.1038/srep35077)
    - Faster switching equals faster information storage and transfer
    - However, unlike ferromagnetic materials, this switching cannot be achieved very easily with external magnetic fields. Instead, we turn to switching using spin transfer torque, where a spin current exerts a torque on the magnetic moments in the antiferromagnet.

- Antiferromagnets do not create stray fields as strongly as ferromagnetic materials will.
    - **Replace ferromagnetic bits:** We could possibly replace the magnetic bits used in memory devices (currently use ferromagnetic material). This would allow us to scale things down even smaller since the antiferromagnetic bits won't interfere as much with one another through creating stray fields. And once again, they switch more quickly, so memory could be written more efficiently. (https://arxiv.org/ftp/arxiv/papers/1611/1611.07027.pdf)

- Additionally, antiferromagnets are less prone to perturbations from outside magnetic fields.
    - **The resilience to outside fields is both a blessing and a bane.** Antiferromagnets can be used more comfortably in devices which contain multiple components surrounding the magnetic material, since it is less likely to both be perturbed by and perturb these surrounding components.
        - However, this resilience makes antiferromagnets notoriously hard to manipulate when we want to put them to use. **How do we manage to both write and read out the antiferromagnetic ordering?**
            - **Antiferromagnets do respond to some stimuli:** Stimuli includes spin hall effect, magneto optical kerr effect (since it is a quadratic

effect, shows up even with net zero magnetization), and anisotropic magnetoresistance (AMR, depends just on direction of current to the magnetic ordering direction). However, these effects give small signals, hard to detect above thermal noise.

- Spin orbit torque, described earlier, is one avenue at least for adjusting antiferromagnetic ordering. Basically, we use electrical currents to do the switching, rather than magnetic fields like seen in traditional HDD and MRAM storage. Spins exert torque on magnetic moments, redirecting the Neel vector. (https://beach.mit.edu/antiferromagnetic-spintronics/)
- We could use interface coupling between a soft ferromagnetic layer and an antiferromagnetic layer. The ferromagnet can be switched, which then exerts a force on the antiferromagnet to switch as well. But this is no longer a purely antiferromagnetic device. (https://doi.org/10.48550/arXiv.1509.05296)
- Antiferromagnets with weak ferromagnetism may be useful. The weak ferromagnetism is a result of broken symmetry, intrinsic to the material, does not rely on ferromagnetic impurities. This weak ferromagnetism could be used as a means to switch the material's ordering. Of course, a stray field is then produced, but not as strong as a purely ferromagnetic material still.

- If we have an antiferromagnet with degeneracy in its magnetic ordering, we can read out more than one state for its ordering. But this can be difficult to control directly due to the aforementioned resilience to outside fields.

- **Conclusion**
  - The industry tendency so far has been to push to smaller and smaller dimensions for our electrical devices so that we may fit more data into smaller areas. This process is becoming increasingly costly and formidable though. Beside our technological limitations to making things smaller (such as resolution for printing features with photolithography), we are contending with quantum mechanical effects such as tunneling and uncertainty, limiting our precision. We need new approaches to data storage, since there is no way around these problems.
  - Antiferromagnetic materials in the field of Spintronics are a topic of great excitement and potential for the future of data storage and transfer. They can be scaled down due to their net zero magnetization, and fast dynamics allows them to surpass current technologies. Although they show great potential, there are many challenges yet to be overcome in ways that allow them to be practically implemented into everyday devices. Scientists work hard at designing and

discovering new ways to effectively switch and read out states from these materials.

- With so many leaps in our understanding of spintronics with respect to antiferromagnets in recent times, the future looks promising for this class of materials. They may allow us to make the next jump beyond current burgeoning technologies such as MRAM.