Application Note 1087-203

Measuring the inverse spin Hall effect (ISHE) using the PPMS/DynaCool/VersaLab

The inverse spin Hall effect (ISHE) is discussed in the Application Note “Introduction to: Broadband FMR Spectroscopy” (1087-201). In summary, if we consider a ferromagnet/non-magnetic bilayer (*e.g.* $Ni_{80}Fe_{20}$/Pd) undergoing a resonant precession, a diffusive flow of spins from the $Ni_{80}Fe_{20}$ ferromagnet will enter the non-magnetic Pd layer due to a phenomenon known as spin pumping [1]. Then, via the inverse spin Hall effect (ISHE) [2], which can be significant in non-magnetic layers with a large spin-orbit interaction (*e.g.* Pt, W, Pd, *etc.*), this diffusive flow of spins will be converted into a measurable transverse DC voltage. A special coplanar waveguide (CPW) (4087-638-01, 02, 03) was developed for the room temperature only configuration that integrates additional electrical contacts for measuring this ISHE generated voltage (V_{ISHE}).

This Application Note describes how to use a new CPW (4087-608) suitable for the CryoFMR probe available for the PPMS/DynaCool/VersaLab platforms, shown below in Figure 1(a). The two additional ISHE contact pads run parallel to the CPW and have a center-to-center separation of 3.5 mm. Each pad has five raised bumps to help facilitate electrical contact to the sample and are connected to pins 10 and 12 of the Grey LEMO connection via the standard sample chamber wiring. Note, a single additional auxiliary connection to pin 7 is also provided and could be used to *e.g.* voltage bias a sample with an external voltage supply.

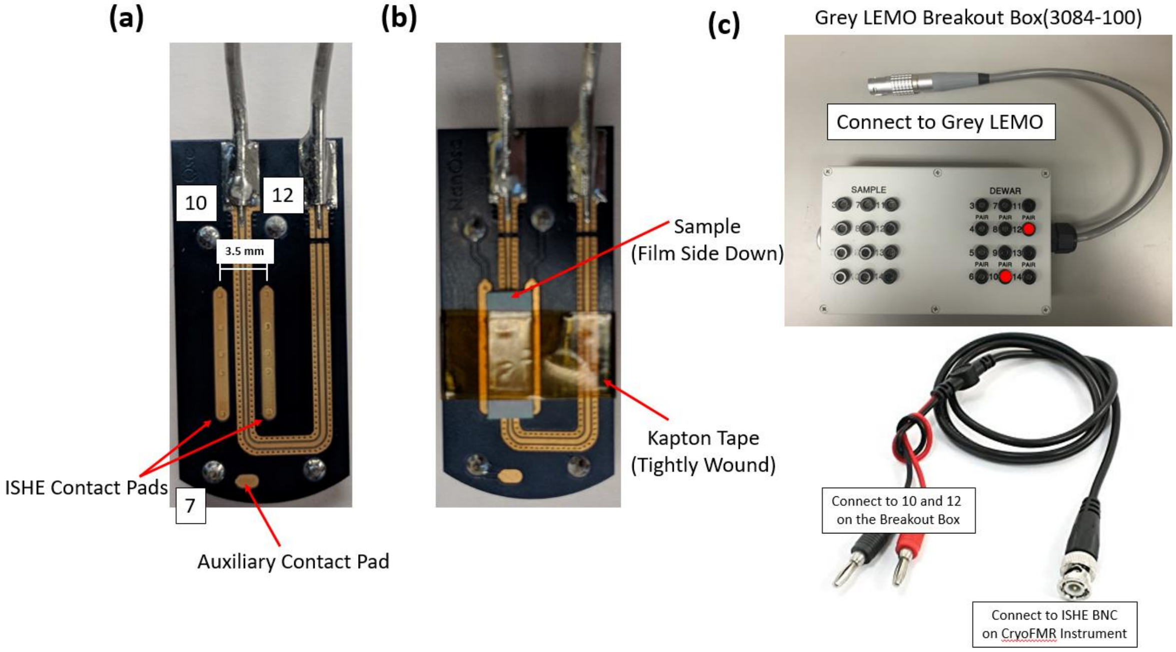

Figure 1. (a) CPW with additional ISHE contact pads. (b) Placement of the test sample on the CPW using *tightly* wound Kapton tape. (c) Additional equipment needed to route the ISHE voltage from the Grey LEMO to the NanOsc CryoFMR instrument.

The test sample used in this Application Note is a $Ni_{80}Fe_{20}$(10 nm)/Pd (5 nm) bilayer sputter deposited on a thermally oxidized Si substrate. It is placed film-side down straddling the ISHE contact pads and *tightly* held in place using Kapton tape, as shown in Figure 1(b). The ISHE voltage across pins 10 and 12 must then be routed to the ISHE input BNC on the front panel of the CryoFMR instrument. One route to accomplish this would be to use the Quantum Design breakout box (3084-100), Figure 1(c, top). Simply connect the LEMO connector on the “Dewar” half of the breakout box to the Grey LEMO connector of the PPMS/DynaCool/VersaLab. One can then use a common and customer supplied BNC-to-banana adapter, an example is shown in Figure 1(c, bottom), to connect the breakout box to ISHE input BNC on the front panel of the CryoFMR instrument.

An important first step before measuring the ISHE response, is to first map out the conventional FMR spectra as the ISHE voltage should closely follow the FMR. An example spectrum, measured at 10 GHz for the $Ni_{80}Fe_{20}$(10 nm)/Pd (5 nm) test sample, is shown in Figure 2(black squares) exhibiting the expected resonant field for a 10nm thick $Ni_{80}Fe_{20}$ film.

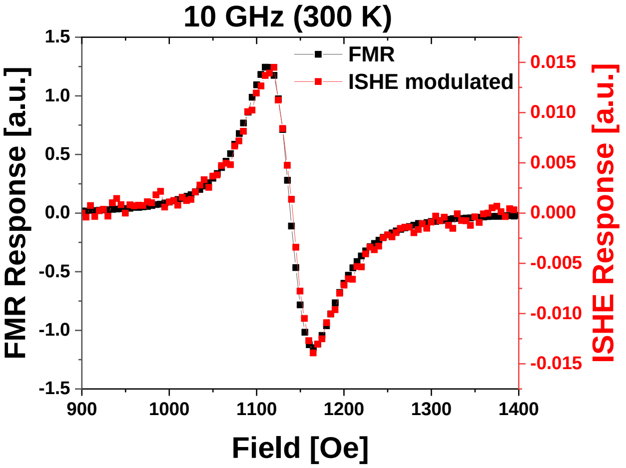

Figure 2. Comparison of the traditional FMR and ISHE responses of the $Ni_{80}Fe_{20}$(10 nm)/Pd (5 nm) test sample.

The ISHE voltage (V_{ISHE}) is measured using the same lock-in amplifier used to measure the FMR response. However, for ISHE measurements two different modulation schemes are provided. In both schemes the lock-in amplifier will filter out an AC signal in sync with the set modulation frequency. One can either *(i)* modulate the external field using the provided Helmholtz coils, as is done when measuring the FMR response, or *(ii)* chop/pulse the V_{ISHE} using an internal relay. The first scheme measures the field derivative of the ISHE voltage to determine the line width and the resonance field, in the same way as for an FMR measurement. However, the derivative carries no information about the DC voltage. The chopping method requires no field modulation, but instead chops the ISHE DC signal to create a square wave that the lock-in detector can measure. Again, the line width and resonance field can be extracted. The chopping relay adds an offset to the read-out so the DC voltage level also cannot be determined with this method. The notch filters should be enabled and the bandpass filter should be enabled only if a 490 Hz modulation is used.

The detector mode can be changed by entering *Settings* and selecting either *ISHE modulated* or *ISHE chopped.* The *ISHE modulated* signal measured at 10 GHz for the $Ni_{80}Fe_{20}$(10 nm)/Pd (5 nm) test sample, is shown in Figure 2(red squares) and closely mimics the more standard FMR response in terms of resonance field and linewidth, albeit with a smaller amplitude. Figure 3 compares the *ISHE modulated* and *ISHE chopped* detection schemes discussed above at 6 GHz for the same test sample. Note that while the *ISHE modulated* response has the characteristic derivative-like curve shape, the pulse-modulated signal exhibits a single absorption peak as it shows the direct (non-derivative) ISHE voltage. Depending on the modulation strength the chopped signal often will exhibit an increased signal strength and improved SNR as compared to the field-modulated signal.

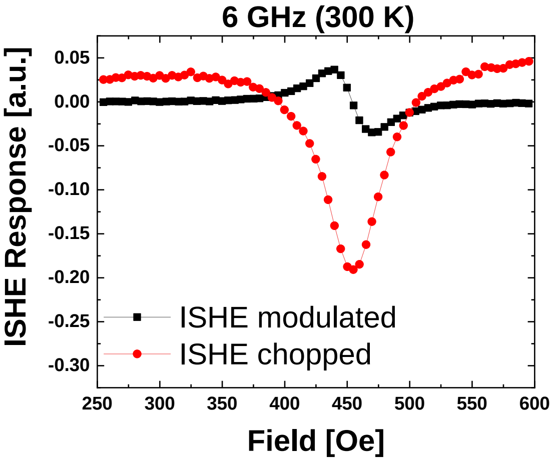

Figure 3. Comparison of *modulated* and *chopped* ISHE detection schemes for the $Ni_{80}Fe_{20}$(10 nm)/Pd (5 nm) test sample.

Finally, temperature dependent measurements are shown in Figure 4 for the ISHE test sample measured at 3 GHz comparing data taken at 300 K (black squares) and 5 K (red circles). Note the decrease resonance field at 5 K, consistent with an increase in magnetization of the $Ni_{80}Fe_{20}$ layer.

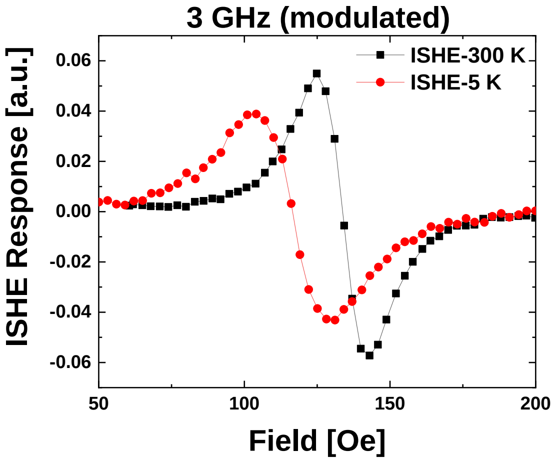

Figure 4. The ISHE voltage measured at 300 K (black squares) and 5 K (red circles) for the $Ni_{80}Fe_{20}$(10 nm)/Pd (5 nm) test sample.

References

[1] Y. Tserkovnyak, A. Brataas, G.E.W Bauer, "Enhanced Gilbert damping in thin ferromagnetic films", *Physical Review Letters* **88**, 117601 (2002).

[2] J.E. Hirsch, "Spin Hall Effect", *Physical Review Letters* **83**, 1834 (1999).