Multi-level Magnetic Tunnel Junctions with Crossing-Ellipse Free Layers

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Motivation and Objectives

A magnetic memory cell stores one bit: the free layer is either parallel or antiparallel to a fixed reference layer. A cell holding more remanent directions stores more per unit area — and, as a neuromorphic synapse, holds a weight with more than two values [5]. That is the multi-level tunnel junction, or M²TJ, that MultiSpin.AI is built on [1,2].

This work fabricates two, three and four crossing ellipses, measures how many resistance levels they hold, and reproduces them in micromagnetics [4].

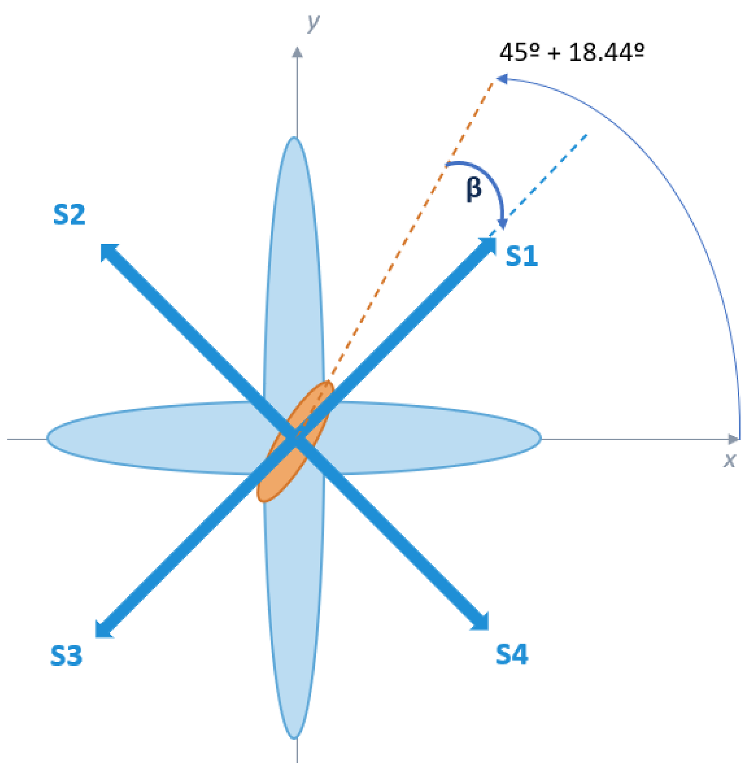
The interest is not only density. A junction holding several remanent levels is a non-volatile analogue weight, and a crossbar of them performs a neural network's multiply-and-accumulate where the data already sits, instead of moving it to a processor and back [5].

The states are remanent, so the weights survive the power being cut and an edge co-processor can sit at zero standby between inferences.

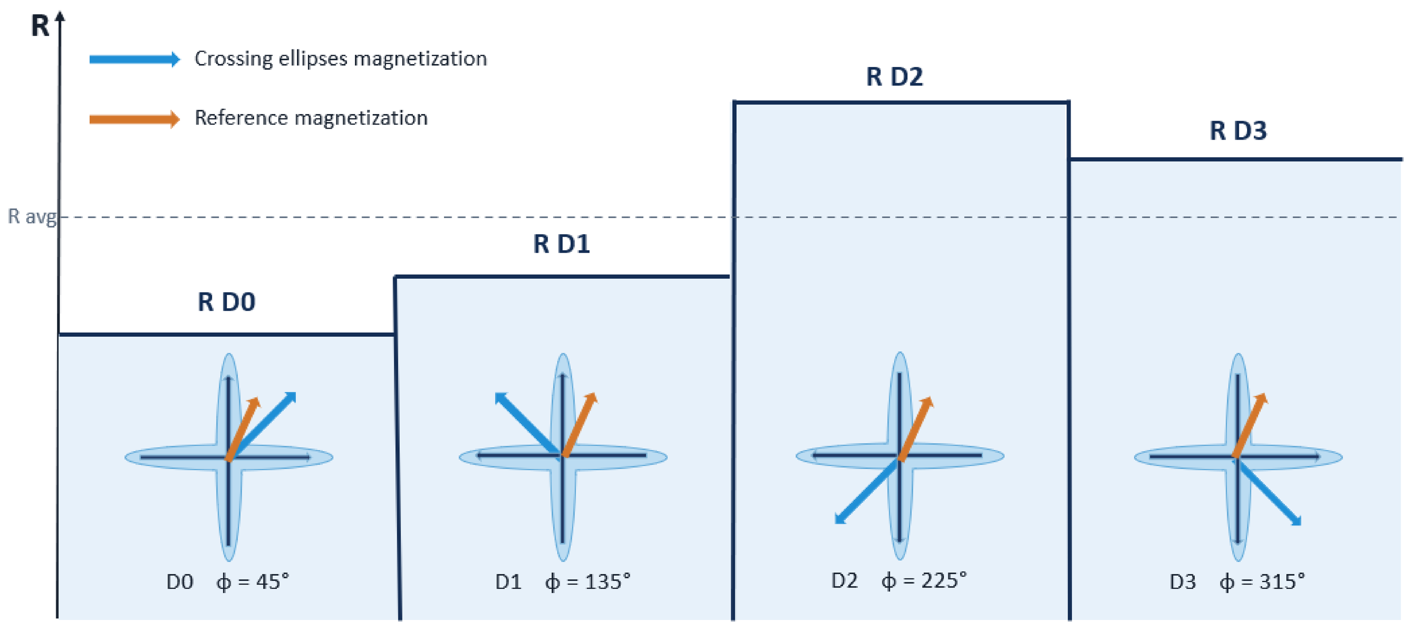
Fundamentals

The directions a free layer can hold are set by its shape.
Crossing two ellipses on a common centre draws two easy axes instead of one, and the magnetisation of the crossing. Settles along one of the four bisectors, S_1 to S_4 [2,3].

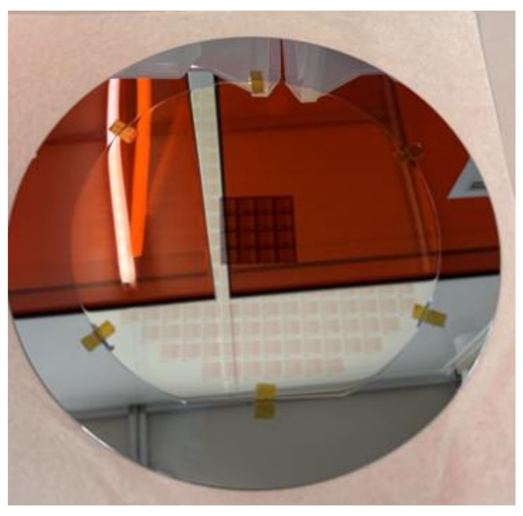
Reading them is a question of angle. The junction resistance follows β, measured between the free layer and the pinned reference above it, so each of the four directions sits at a resistance of its own.

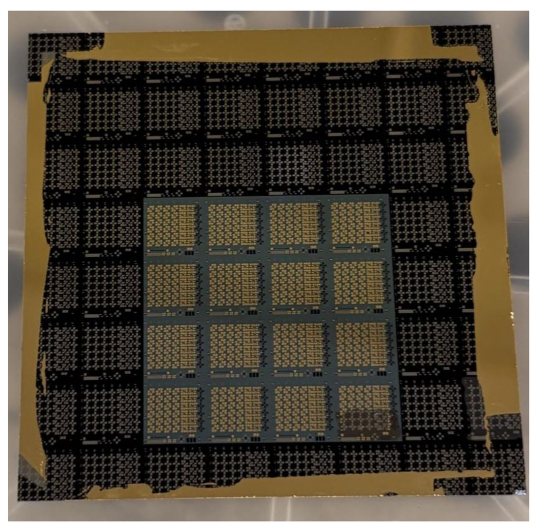


$$R(\theta) = \frac{R_P + R_{AP}}{2} - \frac{1}{2}\Delta R\cos\beta$$

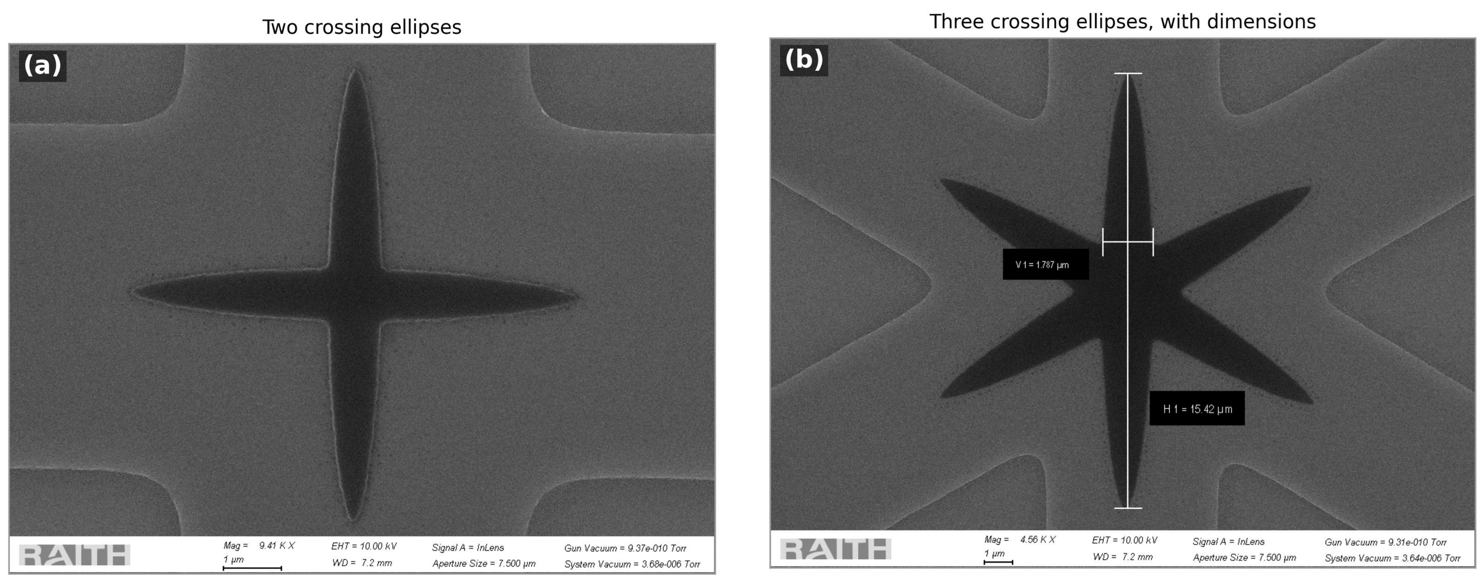


Devices and Fabrication



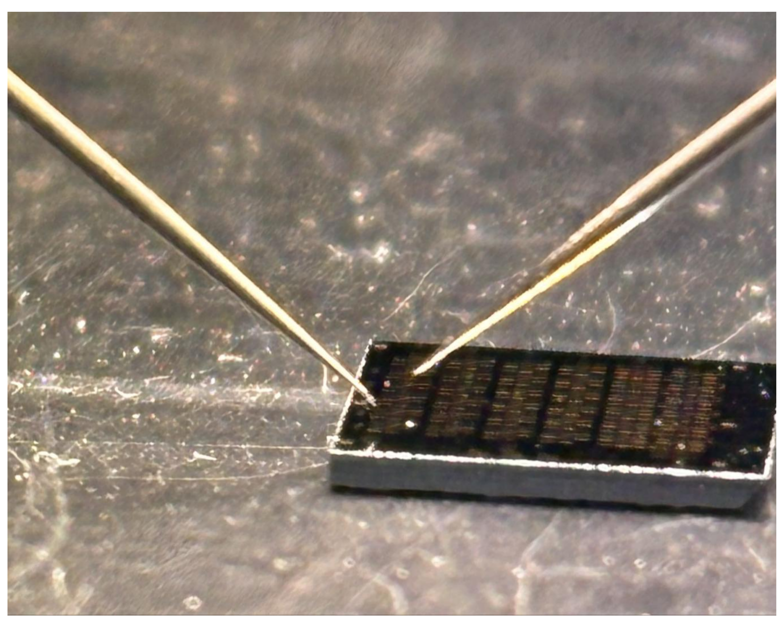


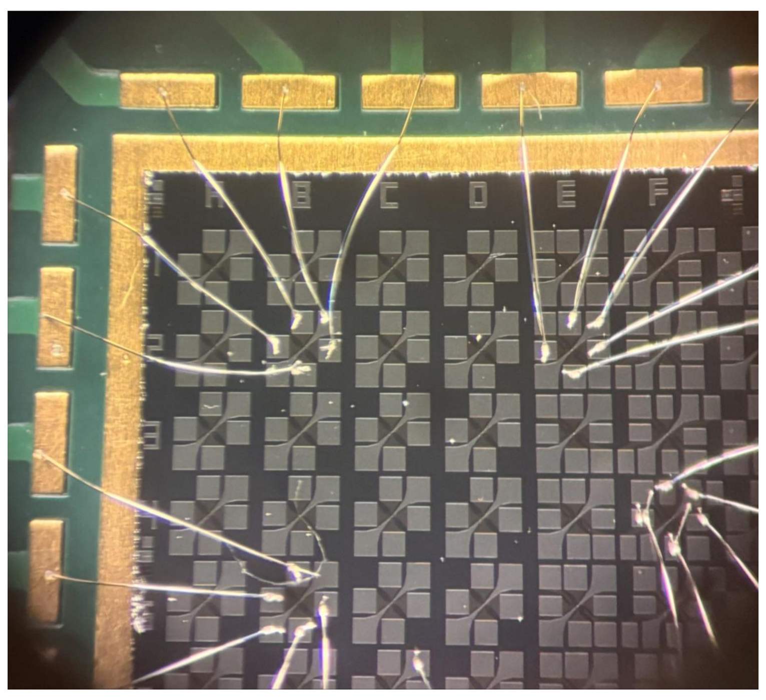
All devices were fabricated in the INESC MN clean room. The stack is deposited by ion beam, and the geometry is then built up in successive steps combining electron-beam and direct-write laser lithography, ion milling, passivation and lift-off.
The crossing ellipses themselves are defined by the electron-beam step, while the laser lithography defines the electrodes that contact them.



(a) Two crossing ellipses; (b) Three crossing ellipses. Both geometries were fabricated and measured

Experimental Results





Experimental Setup

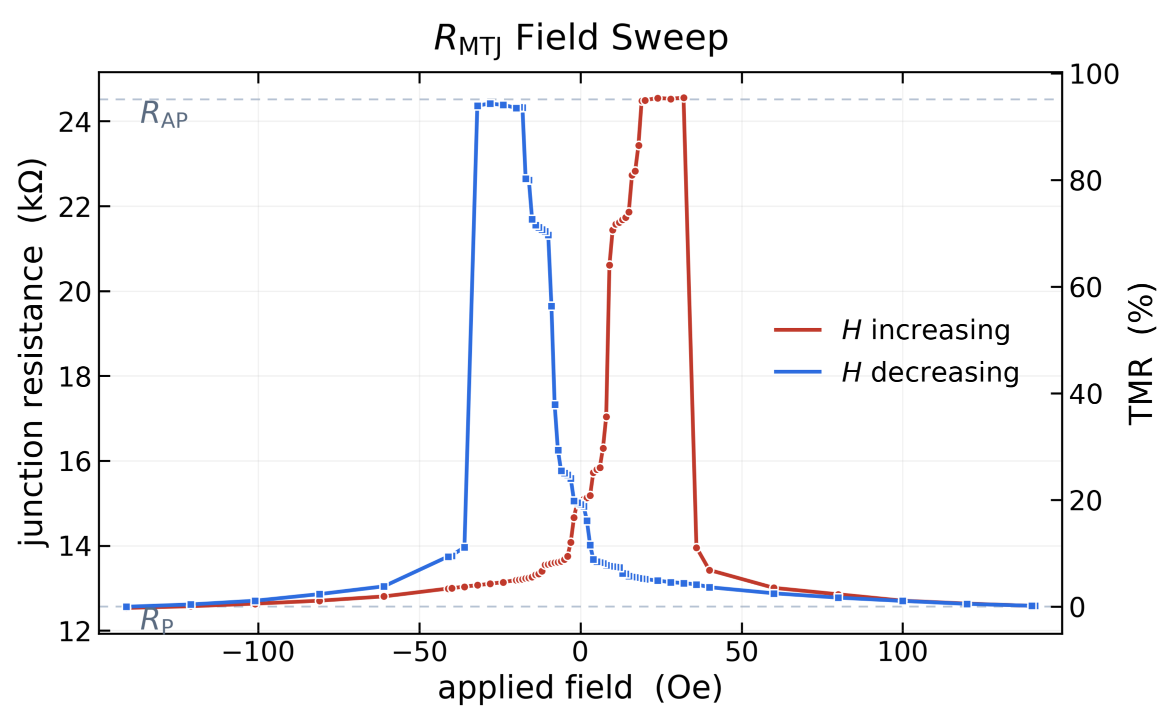
- **Electrical Characterisation**:
  - Voltage/resistance read by a nanovoltmeter on a probe station.
  - Automated sample rotation controlled by a motorized stage.

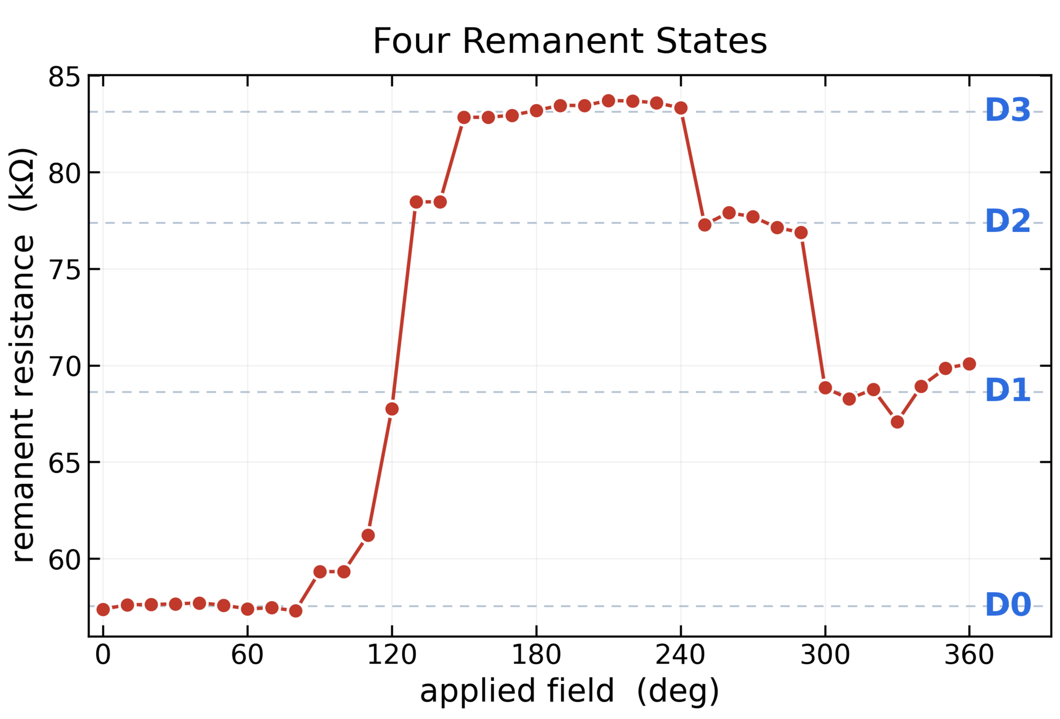
Measurement Protocol

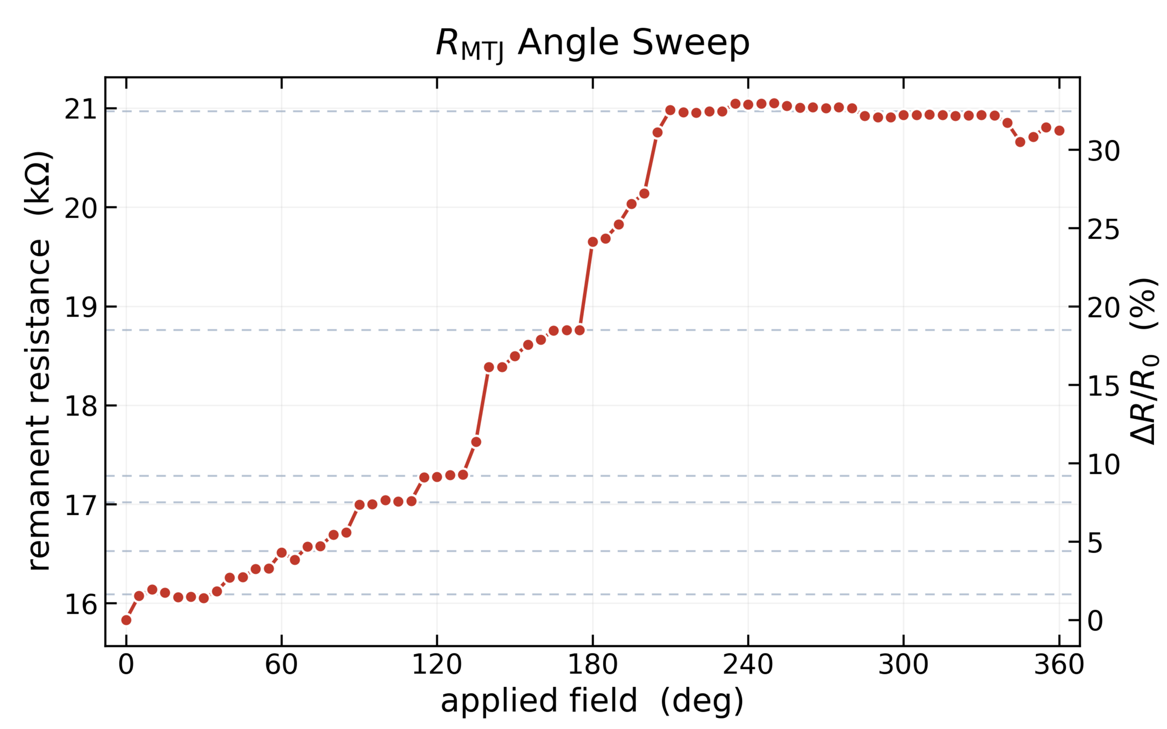
- **Field Sweep (Fixed Angle)** confirms proper tunnel barrier integrity and rules out pinhole short circuits.
- **Angle Sweep at Remanence (Fixed Field)**
  - Field applied at a set angle, **turned off**, and junction resistance measured at zero field.

Observed State Counts:

- **2 Ellipses**: Resolves **4 discrete states** (as shown in R_{MTJ} field/angle plots).
- **3 Ellipses**: Resolves **at least 6 discrete states**.







Conclusions

- Crossing ellipses give four stable remanent states, written by field angle alone and read directly in a working tunnel junction.
- The field sweep is the control: parallel and antiparallel differ by 95 %, so the barrier is intact.
- The angle sweeps are the result: write with the field at an angle, read at zero field — four levels with two crossing ellipses, six with three.
- Writing them by spin–orbit torque instead of field is the next step [1,3].

Acknowledgements
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