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Breakthrough in current-in-plane tunneling measurement precision by application of multi-variable fitting algorithm

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We present a breakthrough in micro-four-point probe (M4PP) metrology to substantially improve precision of transmission line (transfer length) type measurements by application of advanced electrode position correction. In particular, we demonstrate this methodology for the M4PP current-in-plane tunneling (CIPT) technique. The CIPT method has been a crucial tool in the development of magnetic tunnel junction (MTJ) stacks suitable for magnetic random-access memories for more than a decade. On two MTJ stacks, the measurement precision of resistance-area product and tunneling magnetoresistance was improved by up to a factor of 3.5 and the measurement reproducibility by up to a factor of 17, thanks to our improved position correction technique. © *2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* https://doi.org/10.1063/1.4989994

I. INTRODUCTION

Four-point probe (4PP) electrical characterization of thin films has been used for decades in industry and research.[1] The introduction of micro-four-point probe's (M4PP's)[2] opened the possibility of characterizing thin films with sub-mm lateral dimensions[3] and performing resistance mapping with high spatial resolution.[4,5] The miniaturization of 4PP's has also enabled development of new metrology methods such as the micro-Hall effect for characterization of carrier density and mobility without lithographically defined Hall structures.[6] In addition, M4PP has proven particularly useful for characterization of layered structures where the characteristic length scale that describes the current flow is comparable to the inter-probe distances, such as the current-in-plane tunneling (CIPT) method for magnetic tunnel junction (MTJ) stacks[7] and junction leakage measurements,[8] both relying on the principles first described by Severin[9] and Vu.[10]

The CIPT method is extensively used world-wide for characterization of MTJ stacks and can be used to evaluate the resistance-area (RA) product as well as the tunneling magnetoresistance (TMR), right after the deposition of the stack without any further processing. The CIPT method relies on M4PP measurements with a variable electrode pitch, traditionally performed with a multi-electrode probe comprising 8–12 collinear electrodes, thus allowing the user to choose sub-probes of four electrodes with a different mean electrode pitch[7] [see Fig. 1(a)]. The precision of M4PP measurements is limited by position errors that occur when each electrode gets in contact with the sample surface, where the actual electrode positions will differ from the nominal positions, thus introducing a measurement error. For a single conductive sheet (infinite in lateral extension as well as for small test pads), this dominant source of geometrical measurement error can be eliminated by van der Pauw type position correction,[3,11]

where the four-point resistance is measured in two electrode configurations and the sheet resistance is found independent of the electrode positions assuming the electrodes are placed on a straight line, i.e., correcting for in-line position errors. Worledge successfully applied a first order van der Pauw type position correction to the CIPT method to increase precision even though the single sheet assumption does not hold true for MTJ's.[12] For industry relevant MTJ samples, this position correction improves the precision on RA of about a factor of 5, compared to uncorrected CIPT measurements.[13] Currently, this first order position correction represents the industrial and research state of the art for CIPT measurements.[12,14] In the 100 yr history of four-point probe measurements, all the proposed methods for electrode position correction have been based on different van der Pauw type corrections, but in this work we present a novel concept that finally solves the problem for length scale dependent samples that are not a single conductive sheet. Our method adapts to the actual analytical model used to describe the measurement and is not assuming the sample to be a single infinite sheet. We apply our correction scheme to the CIPT technique and demonstrate highly improved measurement precision (up to 3.5 times better on the precision and 17 times on the reproducibility) on RA and MR compared to the current state of the art. This improvement is achieved by a proper correction for in-line position errors, while off-line errors, which are of second order, remain uncorrected.

II. THEORY

The CIPT model describes a single tunneling barrier MTJ stack as two conductive sheets separated by a thin tunneling barrier. The model defines the transfer length $\lambda = \sqrt{RA_{low}/(R_t + R_b)}$, typically on the order of 1 μm, where RA_{low} is the resistance area product in the low resistance
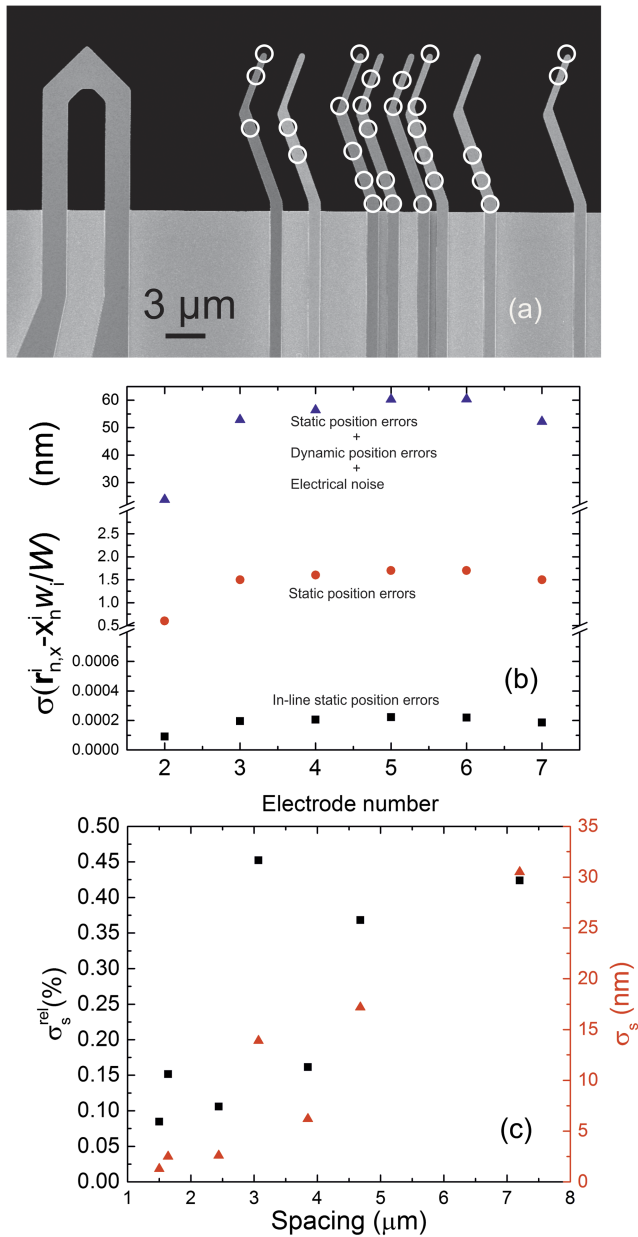
FIG. 1. (a) Micro-8-electrode probe (M8PP) with a strain gauge for precise landing. The white circles indicate 7 different 4-electrode sub-probes. (b) The standard deviation of the difference between the true electrode positions and the corresponding fitted values, calculated over 200 simulated CIPT measurements on wafer 2. (c) The (relative) standard deviation of the difference between the true spacing and the fitted ones. Triangles refer to the right axis. The simulations are run for wafer #2 and the applied noise sources are σ_{static} = 10 nm, σ_{dynamic} = 2 nm, and $\sigma_{\text{elec. noise}}$ = 32.5 $\mu\Omega$.

state, R_t and R_b are the sheet resistances of the top and bottom conductive layers, respectively. The transfer length λ describes the transition from the current transport in the top sheet only to transport in both sheets in parallel. The tunneling magnetoresistance is defined as TMR = (RA$_{\text{high}}$ − RA$_{\text{low}}$)/RA$_{\text{low}}$, where high and low indicate, respectively, the high resistance and low resistance states of the junction resulting from the spin polarized tunnel current and the magnetic states of the top and bottom electrodes. Finally, the M4PP resistance values using four of the electrodes are described by the model

$$R_{A(C)}^i = \frac{R_t R_b}{R_t + R_b} \frac{1}{2\pi} \left[\frac{R_t}{R_b} \left(K_0 \left(\frac{\left| \mathbf{r}_{2(4)}^i - \mathbf{r}_1^i \right|}{\lambda} \right) - K_0 \left(\frac{\left| \mathbf{r}_3^i - \mathbf{r}_1^i \right|}{\lambda} \right) \right) \right.$$
$$\left. - K_0 \left(\frac{\left| \mathbf{r}_4^i - \mathbf{r}_2^i \right|}{\lambda} \right) + K_0 \left(\frac{\left| \mathbf{r}_{4(3)}^i - \mathbf{r}_{3(2)}^i \right|}{\lambda} \right) \right) - \ln \left(\alpha_{A(C)}^i \right) \right],$$

(1)

where

$$\alpha_{A(C)}^i = \frac{\left| \mathbf{r}_3^i - \mathbf{r}_1^i \right| \left| \mathbf{r}_4^i - \mathbf{r}_2^i \right|}{\left| \mathbf{r}_{2(4)}^i - \mathbf{r}_1^i \right| \left| \mathbf{r}_{4(3)}^i - \mathbf{r}_{3(2)}^i \right|}$$

(2)

when A and C configurations are used.[14] Here, $\mathbf{r}_n^i$ are the electrode position vectors, $n \in \{1,2,3,4\}$ is the electrode number of the *i*th sub-probe, cf. Fig. 1(a). Typically, the electrodes are placed in-line, which implies that the in-line position errors are the main source of geometrical errors, whereas off-line position errors give a second order contribution. In order to extract the relevant MTJ parameters, RA and MR, from the resistance values measured using a series of M4PP measurements at a different mean pitch, the model parameters and predicted resistance values are fitted against the measured resistances using a least square error algorithm. In the fitting operation, four parameters are fitted: RA, MR, R_t, and R_b. Conventionally, as Worledge proposed,[12,14] dual configuration resistances are defined by the simple linear combination of the resistances measured in A and C configurations for each sub-probe to obtain a more precise result. Minor improvements can be obtained by applying the non-linear van der Pauw correction.[13] The method we propose simultaneously fits not only the aforementioned four CIPT parameters but also the in-line positions of all electrodes at each given probe-to-surface engage. Thus, the in-line position correction is integrated directly into the minimization of the error between the measured resistance values and the resistance model.[15] In mathematical terms, this can be expressed by the minimization of the error,

$$\varepsilon = \sum_{n=1}^{m} \left(f(\alpha, \beta_n) - R(\beta_n) \right)^2,$$

(3)

where the first term in the sum $f(\alpha, \beta_n)$ represents the model predicted resistances and the second term $R(\beta_n)$ represents the corresponding measured resistances. f is the resistance model function, α represents a vector containing the electrical sample parameters, and β_n represents a vector containing the positions of the four probes used in any independent measurement n, whereas m is the number of independent measurements used. This equation implements a multi-variable least square data fit method to extract at the same time the relevant electrical sample parameters α and the actual positions of the electrodes β_n. This methodology is relevant for all four-point probe measurements where the resistance model of the sample f differs from that of a simple single sheet (the only case for which a perfect in-line position correction can be currently made with van der Pauw type corrections).

By using this error minimization, we can apply the proper resistance model adapted to the sample under test. In the case of CIPT (i.e., for MTJ samples), if all the electrode positions are free to be fitted, there is no fixed length to determine the physical length scale of the sample λ correctly. In fact,

a compression or an expansion of the total width of the probe due to position errors would be equivalent to a shift in the λ value. Due to this effect, the distance between the two outermost electrodes is assumed fixed (this is the most accurate inter-electrode distance).

III. RESULTS AND DISCUSSION

We used Monte Carlo (MC) simulations of the CIPT measurements to prove that the proposed position correction method correctly computes the spacing between electrodes and thus effectively realizes the position correction. Simulated resistance values in A and C configurations were calculated using Eq. (1) for each of the 7 sub-probes with a normally distributed position error added to each electrode position for each engage (i.e., probe landing). Thus 14 resistance values were calculated for each engage, i.e., A and C configuration resistances for each of the 7 sub-probes. In the simulations, we added both static and dynamic in-line and off-line position errors; σ_{static} is set to 10 nm in both directions, whereas σ_{dynamic} is set to 2 nm in both directions as well (for the definitions of static and dynamic position error, see Ref. 14). The simulated resistance values were then fed to our multivariable fitting routine that minimizes the error in Eq. (3) and computes the four CIPT parameters and the electrode positions which are not fixed. From the MC simulations, we can evaluate how accurately the fitting routine estimates the electrode positions and the electrode spacing. In order to quantify the performance, first we calculate all the differences $r^i_{x,n} - x^i_n w_i/W$, where $r^i_{x,n}$ is the in-line (i.e., x) position component of the nth electrode for each simulated engage i and x^i_n is the fitted electrode position normalized by the factor w_i/W, where w_i is the engage dependent total probe width (i.e., $\left| r^i_{x,8} - r^i_{x,1} \right|$) and W is the nominal total probe width (24.38 μm). This normalization is needed to take into account that a contraction or expansion of the probe width cannot be detected by the fitting routine since it assumes a fixed probe width of 24.38 μm. This normalization is equivalent to using the actual probe width $\left| r^i_{x,8} - r^i_{x,1} \right|$ as an input value for each fitting (i.e., for each engage). Figure 1(b) shows that when only the in-line static position errors are applied, the standard deviations of the position difference $\sigma \left(r^i_{x,n} - x^i_n w_i/W \right)$ for each electrode are virtually zero. This fact demonstrates how the proposed position correction method realizes an exact (within numerical error) position correction of in-line static position errors. When an off-line component of the static position errors is also included in the MC simulations, the position correction method estimates the electrode position with an error smaller than 2 nm. When all the noise sources are included, i.e., normally distributed in-line and off-line static and dynamic position errors as well as the electrical noise ($\sigma_{\text{elec. noise}} = 32.5 \ \mu\Omega$), the error on the estimated electrode positions is significantly higher, i.e., a higher standard deviation of the position difference up to 58 nm. Here, it is important to notice that the position differences $r^i_{x,n} - x^i_n w_i/W$ within a single engage i are correlated. In fact, the standard deviation on the difference between the actual spacing for each engage and the fitted spacing, σ_s, shown in Fig. 1(c), is much lower than those on the single electrode position. In particular, for the three smaller

spacing values, which suffer most from geometrical errors, the standard deviation is a few nanometers (and the relative standard deviation is below 0.15%). The fact that the proposed position correction method very precisely computes the three smaller spacing values for each engage implies that the sub-probes with small mean pitches are only lightly affected by position errors. This is the reason why we see such a drastic improvement in the precision of the CIPT parameter estimates.

Measurements with four CIPT A300 probes on two MTJ test wafers were used to demonstrate the large improvement on the precision and reproducibility obtained by the proposed position correction method. The probe comprises of 8 Au coated silicon dioxide electrodes with variable spacing and a strain gauge surface detector [see Fig. 1(a)]. A fully automatic cleanroom compatible A300-CIPTech tool was used to acquire the data, and the CIPT parameters of the wafers used to demonstrate the improved performance of the CIPT metrology are summarized in Table I.[16]

TABLE I. CIPT wafer parameters.

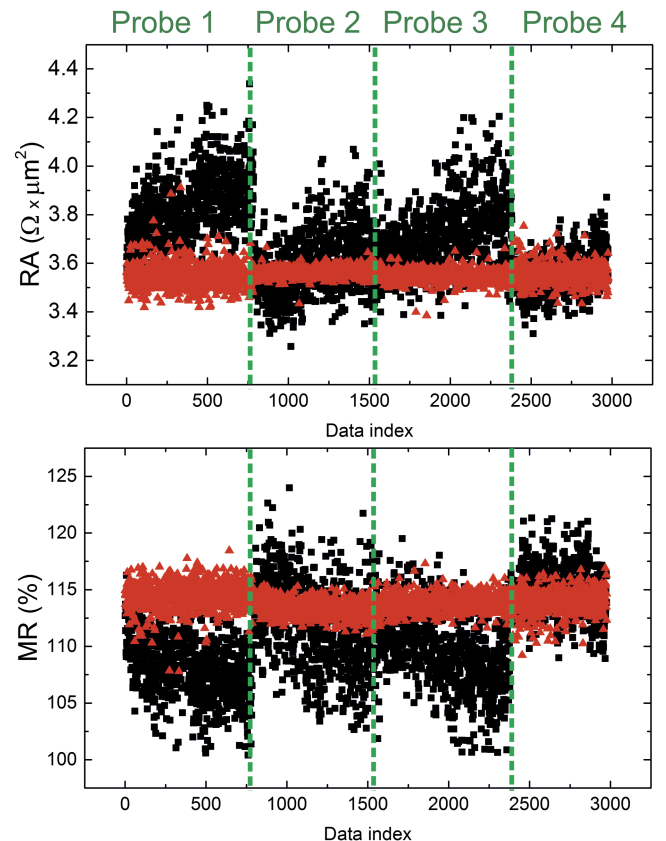| Wafer	R_t (Ω)	R_b (Ω)	RA ($\Omega \ \mu m^2$)	λ (μm)	MR (%)
#1	15.5	1.1	9.7	0.76	130
#2	15.5	1.1	3.6	0.46	125

FIG. 2. RA and MR data acquired with 4 M8PP-A300 probes on wafer #2. 750 points per probe were acquired. The black squares represent the data obtained using the standard position correction method; the red triangles represent the data obtained using our position correction method.

Each probe measured approximately 750 distinct locations all located in an area of $(240 \times 150 \ \mu m^2) \times 4$ on both MTJ samples. Since the area is very small, sample variations across the area are not expected to influence the results. In each engage, A and C configuration resistances were measured for each of the 7 sub-probes, i.e., 14 independent measurements per engage as we also used in the simulations. In Fig. 2, the data for the test wafer with the smallest RA are shown (test wafer #2). The black squares are the results for the two CIPT parameters when the standard position correction method is used, whereas the red triangles represent the CIPT results when our CIPT dedicated position correction is used (see Fig. 2). Over the four probes, the average precision values are 2.7% for RA and 3.3% for MR for the standard approach, whereas they are 0.9% and 0.8%, respectively, when the CIPT dedicated position correction method is used; this corresponds to a factor of 3.5 improvement of the precision. If we assume the probe to probe reproducibility defined as the relative standard deviation of the four mean values (from the four probes), the CIPT dedicated position correction method delivers a 17 times improvement in the probe to probe reproducibility of RA and 6.5 times improvement on the probe to probe reproducibility of MR; this reduces the maximum relative difference between probe to probe mean values to 0.2% for RA and

0.4% for MR from 3.4% to 2.6%, respectively. The same statistics were computed from the data on test wafer #1 as reported in Fig. 3, giving 5.6 and 2 times improvements in the reproducibility for MR and RA, respectively. For both test wafers, there are vast improvements both in terms of precision and probe to probe reproducibility. In particular, the precision for both the RA and MR is better than 1% over 750 data points, and the probe to probe reproducibility is better than 0.5%.

IV. CONCLUSIONS

The data presented demonstrate how the proposed position correction method can drastically improve the performance when applied to the CIPT technique, enabling unprecedented precision for the characterization of magnetic tunneling junction stacks. Monte Carlo simulations demonstrate how the proposed method, for the first time, is able to precisely estimate the in-line spacing between the electrodes with an error of less than 1.5 nm for the smaller spacing of 1.5 μm, when the M4PP measurements are performed on a MTJ sample. In general terms, the new position correction method opens new possibilities for very precise measurements for a large range of sample types that cannot be described as a single infinite sheet, from MTJ stacks with one or more tunneling barriers to semi-infinite planes for the micro-Hall technique or small pads of multilayered structures.
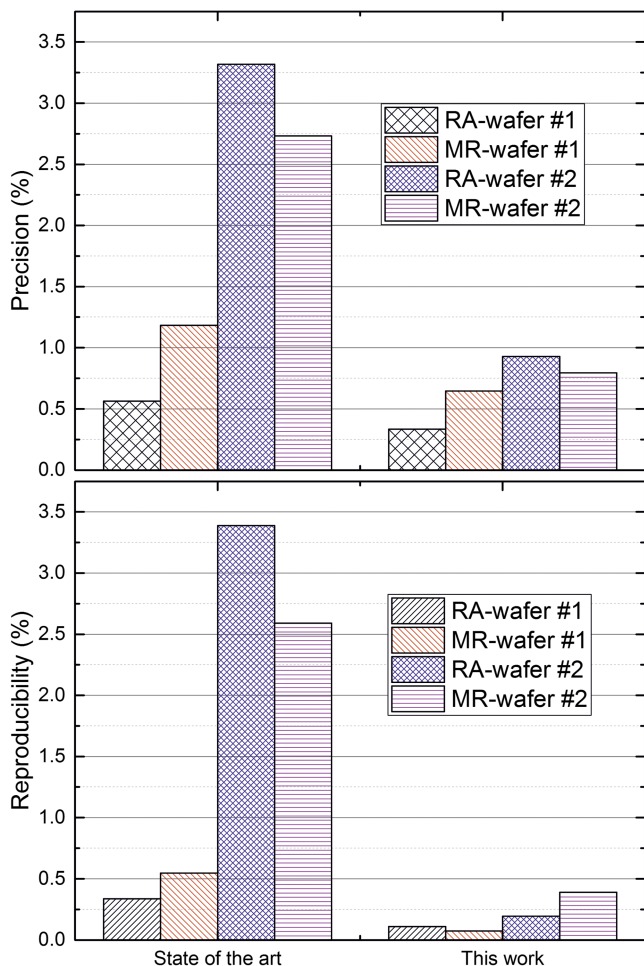
FIG. 3. Precision and reproducibility comparison of the performance using the standard position correction method and using the new position correction method of this work.

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[15] Capres A/S has a patent pending on the new position correction technique.
[16] See www.capres.com for "Capres A/S, Denmark."