

CCEM 2015 INRIM Report

A) Voltage standard and Quantum devices

. In the framework of the EMRP 2012 SIB52 Q-Wave project tasks, a cryocooler was established for operation of pulse-driven JAWS arrays at INRIM. A fully digital platform intended for dynamic characterization of arrays of Josephson junctions to be used in quantum synthesizer was developed and first tests with a lower bandwidth flex cable allowed to observe array steps at different frequencies. The current-voltage characteristic was measured at different frequencies showing the expected constant-voltage steps. Further tests on inductive and resistive dividers to be used for voltage calibration against a Josephson standard have been performed at INRIM. First studies and simulations on a new 10:1 voltage divider and a matched pair of wideband fixed gain composite amplifiers have been performed at INRIM for the new high-speed synthesizer design. a.sosso@inrim.it

NanoSQUIDs made of Nb/Al SNIS Josephson junctions defined with FIB process in a vertical configuration with $0.25 \mu\text{m}^2$ loop area achieving a resolution of $10 \mu\text{B}/\text{Hz}^{1/2}$ have been realized. They can be employed in the field of nanoscale investigations for instance for magnetic nanoparticle sensing. V.Lacquaniti@inrim.it
 Nanosquid of MgB₂ based on nanobridges acting as weak-links have been and fabricated, starting by thin films deposited by co-evaporation process, with two different nanolithography technique. Nanosquid fabricated by EBL and ion milling show a best quality with respect to devices fabricated with FIB technique. E.Monticone@inrim.it
 SET devices have been realized by means of a new technological approach based on the idea of the "suspended island". At the moment, the reproducibility of the method is poor, but the critical technological step, which leads to the random breakdown of the tunnel junctions has been identified to be the passivation of the structure by anodization and an alternative technology for this step is under study. In the framework of the EMRP EXL03 Nanophoton, INRIM developed structures and devices for single photon detection, as possible causes for errors in single electron counting, by conventional double-angle evaporation. G.Amato@inrim.it

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A. Sosso, V. Lacquaniti, P. Durandetto, E. Monticone, M Fretto *Tests of SNIS Josephson Arrays Cryocooler Operation*, Journal J Supercond Nov Magn. DOI 10.1007/s10948-014-(2014)

M.Fretto, E. Enrico, N. De Leo, L. Boarino, R. Rocci, V. Lacquaniti *Nano SNIS Junctions Fabricated by 3D FIB Sculpting for Application to Digital Electronics* IEEE Trans. Appl. Supercond. vol 23, 1101104, 2013.

Granata, C., Vettoliere, A., Russo, R., Fretto, M., De Leo, N., Lacquaniti, V.: Appl. Phys. Lett. 103, 102602 (2013)

C. Granata, A. Vettoliere, R. Russo, M. Fretto, N. De Leo, E. Enrico V. Lacquaniti *Ultra High Sensitive Niobium NanoSQUID by Focused Ion Beam Sculpting* J Supercond Nov Magn DOI 10.1007/s10948-014-2693(2014)

B. Trinchera, A. Sosso, U. Pogliano, V. Lacquaniti, E Monticone, M Fretto, R Rocci, L Roncaglione Tet, D Serazio: *Wideband digital modular system for dynamic characterization of PJVS*, 014 Conference on Precision Electromagnetic Measurements (CPEM 2014), 114-115, 2014.

B) Quantum Hall effect and Graphene-based devices

The modeling of circuits including quantum Hall effect devices has progressed; a 10 kohm quantum Hall array resistance standards including only 12 QHE elements has been published and has been realized by National Institute of Metrology (NIM), China. L.Callegaro@inrim.it

Ortolano M, Abrate M, Callegaro L (2015). On the synthesis of Quantum Hall Array Resistance Standards. METROLOGIA, vol. 52, p. 31-39.

About grapheme, the research steered towards the more established CVD growth onto Cu foils, avoiding the metastability problems affecting films. Monolayer graphene islands up to 0.1 mm in diameter have been obtained, with defect concentration below the detection limit of the Raman technique and mobility values at the top of this class of materials suggesting their suitability for preliminary QHE measurements. To avoid the reduction of mobility related to the transfer method strategies are under study to develop a transfer method able to preserve the film quality. G.Amato@inrim.it

L. Croin, E. Vittone, G. Amato *In situ control of dewetting of Cu thin films in graphene chemical vapor deposition* Thin Solid Film 31 Dec. 2014, vol. 57, Pages 122–127

C) Dc Resistance Electrolytic Conductivityf.

The results of the International comparison EURAMET EM S32 were reviewed and discussed with the pilot Laboratory. A high resistance measurement setup for MOS sensing materials characterization was realized. Results of the construction of the guarded 10×10 G Ω Hamon and of revision and improvement of a measurement system for calibration of current shunts and resistors in dc current in the range from 10 $\mu\Omega$ to 10 m Ω were published.

A National Comparison among INRIM and Secondary accredited Laboratories low resistance at 1 m Ω , 10 m Ω and 100 m Ω level was carried out.

A prototype of thermo-regulated setup involving a 1 Ω and a 10 k Ω Resistance Standards for DMM's and Multifunction Calibrators calibration formed respectively of a net of 10 Ω 10 Ω and 10 Ω 100 k Ω precision resistance elements was developed. P.Capra@inrim.it, f.galliana@inrim.it

In the framework of the EMRP Project ENV05 "Ocean Metrology", besides the Key Comparison CCQM-K105 on Electrolytic conductivity at 5.3 S/m, co-ordinated by INRIM, and the Pilot Comparison CCQM-P142 on equivalence of conductance ratio measurement results of seawater, INRIM took part also in the comparison Deliverable 1.3.6, "Equivalence of conductance ratio measurement results of natural seawater from the Baltic Sea". Moreover, INRiM, in order to answer the needs of the industrial and the clinical sectors, has undertaken activities to extend the traceability of electrolytic conductivity measurements to pure water values (10 $\mu\text{S}/\text{cm}$). The new primary cell for very low electrolytic conductivity measurements was designed and tested. A measurement system with flowing solution was developed to reduce CO₂ contamination at low conductivity values. In this system, a secondary cell can be inserted in series with the primary one for in-line calibration. durbiano@inrim.it

B. Jeckelmann, J.P. Capra, F. Galliana et al. "Final report on supplementary comparison EURAMET.EM-S32: Comparison of resistance standards at 1 T Ω and 100 T Ω ", METROLOGIA, vol. 50, December 2013, ISSN: 0026-1394, doi: <http://dx.doi.org/10.1088/0026-1394/50/1A/01008>

P. Capra, F. Galliana, M. Latino, A. Bonavita, N. Donato, G. Neri "A high resistance measurement setup for MOS sensing materials characterization, book chapter of Sensors and Microsystems: Proceedings - Lecture Notes in Electrical Engineering 268, eds. C. Di Natale, V. Ferrari, A. Ponzoni, G. Sberveglieri, M. Ferrari, pp. 149-154. ISBN: 978-3-319-00683-3 Dicembre 2013

F. Galliana, P.P. Capra, E. Gasparotto, "Traceable Technique to calibrate dc current shunts and resistors in the range from 10 $\mu\Omega$ to 10 m Ω ", Measurement Vol. 46, pp. 1630-1640, 2013.

F. Galliana, P.P. Capra, E. Gasparotto, "10 \times 10 10 G Ω Guarded Hamon Network for the Modified Wheatstone Bridge for High Value Resistors Calibration", IEEE Trans. Instrum Meas., Vol. 62 no.6, pp. 1729-1735, 2013.

F. Galliana, E. Gasparotto "Analysis of a National Comparison in the field of electrical low Dc Resistance". Measurement, vol. 52; p. 64-70, 2014.

A. Zalatarevic et al., Final report of key comparison CCQM - K105 "Electrolytic conductivity at 5.3 S/m", Technical Supplement 2014, Volume 51, 08016, Amount of Substance, doi:10.1088/0026-1394/51/1A/08016 Metrologia.

E. Orrù, F. Durbiano and M. Ortolano, Reference measurement system for low electrolytic conductivity values with a flowing solution, Meas. Sci. Technol. 24 035903, 2013.

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D) Impedance

INRIM is leader of the EMRP 2012 SIB 53 AimQuTE project workpackage "Digital bridges". Within the project, two different bridges for impedance comparisons over the entire complex plane have been realized:

- a digitally-assisted, three-arm current comparator bridge for two terminal-pair impedance comparisons;
- a fully-digital, two-arm voltage ratio bridge.

Both bridges have base accuracy in the 1 ppm range or better and will be employed for an intercomparison with special impedance standards developed by UME, Turkey. First experiments towards four terminal-pair digital bridges are ongoing.

INRIM realized for KRISS a system of two digitally-assisted bridges (ratio bridge and quadrature bridge) for the realization of the farad unit from the quantum Hall effect. Compared with traditional traceability chains, the realized one is simple and automated; the relative uncertainty reached in the calibration of 1 nF capacitors is around 7×10^{-8} .

A ferromagnetic, SQUID-based cryogenic sensor for AC currents has been developed as a feasibility test towards the development of a cryogenic current comparator bridge. L.Callegaro@inrim.it

Callegaro L, D'Elia V, Ortolano M, Pourdanesh F (2015). A three-arm current comparator bridge, for impedance comparisons over the complex plane. IEEE Trans. Instr. Meas., in press. Also on ArXiv:1408.4474

Callegaro L, Kampik M., Kim D B, Pourdanesh (2015) Experiences with a two terminal-pair digital impedance bridge . IEEE Trans. Instr. Meas., in press. Also on ArXiv:1408.2638

Callegaro L., Capra P. P., D'Elia V., Galliana F. (2014). Generation of reference dc currents at 1 nA level with the capacitance-charging method. IEEE Trans. Instr. Meas., vol. 63, p. 1779-1782

E) AC-DC Transfer Standards, AC power

A polyphase measurement digital platform for the construction of a reconfigurable wideband system for power, power quality and energy measurements as well as characterization of PMUs, was completed. The new platform was validated in comparison with the primary power measurement system at power frequencies, and the most relevant results were presented to CPEM 2014. Research activities are being undertaken in order to bridge the gap in terms of power traceability between distorted and sinusoidal signals. For this purpose current and voltage analog transducers are under characterizations and measurement procedures for amplitude and phase calibration have been identified and are being implemented, also for their application in the characterization of the calibrator for PMUs under construction at METAS in the framework of the EMRP 2013 ENG52 Smart Grid 2 project.

An improved version of the wideband polyharmonic synthesizer based on high speed semiconductor technology was completed and an experiment for its calibration by using the concept of direct transfer of high purity quantum waveforms, has been set up and preliminary tests are being carried out.

Participation in the EURAMET Key International Comparison of AC-DC Current Transfer Standards EURAMET.EM-K12. INRiM concluded and sent the results of the measurements at the end of December 2014.

U.Pogliano@inrim.it, B.Trinchera@inrim.it

U. Pogliano, B. Trinchera, and D. Serazio (2014) "A system for the accurate characterization of wideband wattmeters, power quality analyzers and PMUs," CPEM Conf. Dig., Rio De Janeiro, Brazil, pp. 406-407, Aug. 2014.

U. Pogliano, B. Trinchera, M. Lanzillotti, and D. Serazio (2014) "Characterization of resistive dividers for a wideband power analyzer," CPEM Conf. Dig est, Rio De Janeiro, Brazil, pp. 130-131, Aug. 2014.

B. Trinchera, U. Pogliano, "Polyharmonic Digital Synthesis for the calibration of phase sensitive measuring systems up to the ultrasonic band," IEEE Trans. Instrum. Meas., vol. 62, no. 6, pp. 1687 – 1692, June 2013.

F) High Frequency Metrology

Concerning power standard, INRIM operates from dc to 40 GHz with a microcalorimeter in coaxial line, now by using only thermoelectric sensors in 7, 3.5 and 2.92 mm coaxial lines as transfer standards. The system performances have been improved in terms of thermal stability, of HF and LF generator control and of power substitution accuracy between HF and LF. The present measurement method and model is superior respect to amore traditional one in terms of measurement uncertainty from dc to 40 GHz.

In the field of S-parameter measurements, INRIM covers the frequency range from 30 kHz to 110 GHz in coaxial and waveguide transmission lines, but the related CMCs remain limited to coaxial line measurements from 45 MHz to 50 GHz. A comparison between a proprietary software and the METAS VNA Tools has been conducted and on this base, a reliable method to evaluate the measurement uncertainty by means of the METAS software has been established. This method has been applied to the INRIM results in CCEM Key comparison CCEM.RF-K5c.CL. A bilateral comparison concerning S-parameters in the band 50-110 GHz has been conducted with NRC-A*STAR.

Another research activity concerns development of a TDS in the THz gap finalized to dielectric material characterization under an European Research Project. In this framework, a THz Time Domain Spectrometer able to perform measurements in the band 0.3-3 THz has been set-up. l.brunetti@inrim.it, l.oberto@inrim.it

M. Sellone, Y. Shan, Y. S. Meng, L. Oberto, L. Brunetti, N. Shoaib: Comparison of S-Parameter measurements at millimeter wavelengths between INRIM and NMC. IEEE Trans. on Instrumentation and Measurement, Vol. 63, no. 7, pp. 1810-1717, July 2014, doi: 10.1109/TIM.2013.2293227

L. Brunetti, L. Oberto, M. Sellone, E. Vremera: Comparison between Thermoelectric and Bolometric Power Standards. IEEE Trans. on Instrumentation and Measurement, Vol. 62, no. 6, pp. 1710-1715, June 2013, doi: 10.1109/TIM.2013.2253914

G) High voltage and current

A setup for the calibration of direct-current current transformers (DCCT) has been realized and is being employed in the EURAMET.EM-S35 comparison, where INRIM acts as pilot laboratory. C.Cassiano@inrim.it

Callegaro L, Cassiano C, Gasparotto E (2015). On the Calibration of Direct-Current Current Transformers (DCCT). IEEE Trans. Instr. Meas., vol. 64, p. 723-727.

A real-time compensation method for the improvement of the frequency behavior of measurement transducers for transmission and distribution grids has been studied within the EMRP Project ENG52 “Smart Grid II”. The technique relies on the identification of an Infinite Impulse Response digital filter with complex frequency response equal to the inverse of the transducer one, whose parameters are evaluated through a hybrid scheme, based on the combination of stochastic and deterministic procedures. Attention has been focused on the algorithm identification capability, the sensitivity to the weighting array in the optimization cost function and the uncertainty propagation associated with the algorithm input quantities. First applications of the method show an improvement of two orders of magnitude for the ratio and phase errors of the considered transducers from DC to 10 kHz.

Attention has been also focused on the set up of traceable voltage measurement system with analog optical transmission system and on the development of laboratory and portable systems for the calibration of both inductive and low power voltage and current transformers. The calibration setups are equipped with flexible and accurate digital measurement systems enabling the comparison of signals of different kind and order of magnitude from DC up to tens of kilohertz. g.crotti@inrim.it

G. Crotti, D. Gallo, D. Giordano, C. Landi, M. Luiso: “Medium Voltage Divider Coupled With an Analog Optical Transmission System”, IEEE Trans. on IM, Vol. 63, No. 10, 2014.

G. Pasini., L. Peretto, P. Roccato, A. Sardi, R. Tinarelli (2014): “Traceability of Low-Power Voltage Transformer for Medium Voltage Application”, IEEE Trans. on IM, Vol. 63, No. 10, 2014.

H) Electromagnetic fields and EMC

Activity has been carried on within the EMRP Project “Metrology for next-generation safety standards and equipment in Magnetic Resonance Imaging (MRI)”. INRIM has developed advanced mathematical models for the prediction of energy deposition and temperature elevation of human tissues exposed to time-varying magnetic fields of MRI scanners. Attention has been given to the heating caused by RF and gradient coils in patients undergoing MRI and to the spatial correlation between energy deposition and temperature elevation. Problems related to patients with metallic implants have been addressed by evaluating potential dangerous situations in the case of hip prostheses and metallic wires. Experiments have been carried on phantoms to validate the models and establish a level of reliability to be extended to in-vivo simulations. Research has been also devoted to the evaluation of motion-induced fields in human bodies moving within the static magnetic field of a MR tomograph. Specific numerical algorithms have been developed to reproduce induced electrical phenomena in highly detailed anatomical human models assuming realistic motion trajectories in the stray static fields of tubular and open scanners.

As to dosimetry for biomedical devices, activity has been addressed to the analysis of personnel exposure during Transcranial Magnetic Stimulations (TMS). Suitable shields have been studied to reduce the exposure of medical staff. Moreover, mathematical models have been developed and exploited to predict the shielding properties of hybrid ferromagnetic/superconductive structures, suitable to mitigate strong stationary magnetic fields.

Finally in the framework of EMRP Project “Microwave and terahertz metrology for homeland security” models have been extended to account for energy deposition in human tissues and temperature increase in presence of focused beams radiating stratified human tissues. o.bottauscio@inrim.it

As regards electromagnetic compatibility (EMC) the University of Florence and INRIM organized and piloted a proficiency test of radiated emission measurements in the frequency range from 200 MHz to 3 GHz. INRIM participated successfully in two intercomparisons, the first on electric field measurement (CCEM.RF.K24.F) and the second on loop antenna factor (EURAMET.EM.RF-S27), ended in 2013 and 2014 respectively. m.borsoero@inrim.it

L. Zilberti, M. Chiampi, “A numerical survey of motion-induced electric fields experienced by MRI operators”, *Health Physics*, Vol. 105, No. 6, pp. 498-511, 2013, DOI: 10.1097/HP.0b013e31829b4aac

O. Bottauscio, M. Chiampi, L. Zilberti, “Massively parallelized Boundary Element simulation of voxel-based human models exposed to MRI fields”, *IEEE Trans. Magn.*, Vol.50, No.2, 2014, 7025504.

L. Zilberti, O. Bottauscio, M. Chiampi, J. Hand, H. Sanchez Lopez and S. Crozier, "Collateral thermal effect of MRI-LINAC gradient coils on metallic hip prostheses", *IEEE Trans. Magn.*, Vol. 50, No. 11, 2014, 5101704.

A. Trakic, L. Liu , H. Sanchez Lopez, L. Zilberti, F. Liu , S. Crozier, “Numerical safety study of currents induced in the patient during rotations in the static field produced by a hybrid MRI-LINAC system”, *IEEE Trans. on Biomed. Eng.*, Vol. 61 , No 3, pp. 784-793, 2014, DOI: 10.1109/TBME.2013.2289924

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L. Zilberti, A. Arduino, O. Bottauscio, M. Chiampi, "Parametric Analysis of Transient Skin Heating Induced by Terahertz Radiation", *Bioelectromagnetics*, Vol. 35, n. 5, July 2014, pp. 314-323.

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M. Zucca, M. Gamba, F. Fiorillo, “Open screens for local magnetic shielding at low frequencies,”*IEEE Trans. Magn.*, vol. 50, 2014, 8500204.

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C. Carobbi, A. Bonci, M. Cati, C. Panconi, M. Borsero, G. Vizio, “Design, Preparation, Conduct and Result of a Proficiency Test of Radiated Emission Measurements”, *IEEE Trans. on EMC*, Vol 56, No. 6 ,2014.

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F. Pythoud, M. Borsero, D. Bownds, S. Çakir, M. Çetintas, K. Dražil, D. Gentle, D. Giordano, S. Harmon, J. Kupec, Y. Le Sage, B. Mühlemann, M. Ulvr, G. Vizio and D. Zhao, “Final report on EURAMET supplementary comparison EURAMET.EM.RF-S27: “Antenna factor for loop antennas”, Metrologia Technical Supplement, Vol. 51, 01007, 2014, doi:10.1088/0026-394/51/1A/01007.

I) Measurements on magnetic materials

The Magnetics Laboratory of INRIM took part in two international comparison on the magnetic properties of soft magnetic sheets. A first exercise, promoted by the Joint Working Group IEC 68/WG1- ISO/TC17/WG16 (IEC Project IEC TR 68-7), regarded the magnetic losses at power frequencies in grain-oriented Fe-Si sheets (Extended measurement programme: SST Round Robin Test (RRT) and advanced studies of the Epstein to SST relationship). INRIM, acting as pilot laboratory, coordinated the activity of four national metrological laboratories and seven industrial laboratories. The comparison was concluded at the end of 2014. An IEC draft Technical Report (IEC/TR TC 68-7) has been delivered. A second exercise concerned the comparison of measurements in soft magnetic materials at frequencies ranging between 50 Hz and 1 kHz (Supplementary comparison of national standard facilities in the field of measuring the polarization and specific total power loss in soft magnetic materials). The cycle, coordinated by UNIIM and PTB, involved five national metrological institutes (UNIIM, PTB, CMI, NPL, and INRIM). It will end in 2015. F.Fiorillo@inrim.it, V.Basso@inrim.it

Exploiting the setup developed in the framework of the project EMRP ENG 02, investigations have been carried out concerning the ability of some magnetostrictive materials in harvesting the vibrational energy. The principles for the maximization of the electrical power output have been investigated and clarified. The same materials have been investigated for the active vibration compensation of high dynamic forces. m.zucca@inrim.it

O. Bottauscio O., P.E. Roccatto, M. Zucca, “Micropositioning Through Magnetostrictive Actuators,” Sensor Letters, vol. 11, 2013, p. 87-90,

M. Zucca, O. Bottauscio, C. Beatrice, A. Hadadian, F. Fiorillo and L. Martino (2014). A Study on Energy Harvesting by Amorphous Strips. IEEE Transactions on Magnetics, vol. 50, n. 11, 2014, p. 8002104

M. Zucca, N. Fasana, F. A. Raffa, N. Colella, “A simplified vibration compensation through magnetostrictive actuators,” printed online in Journal of vibration and control, 10 pp, 2014, doi: 10.1177/1077546313518956

J) Nanomagnetism

Patterned nanomagnets can be synthesized by selected bottom-up and top-down nanolithography methods. The choice among the different synthesis process is usually determined by application (i.e. nanostructure dimensions and lattice disorder). Dot diameter of the order few nanometers are requested for magnetorecording, while hundreds of nanometers are needed for magnetic sensing. In the latter case, the interest is justified by the presence of unconventional spin configurations like vortex, anti-vortex, bubble, having unique static and dynamic properties. Such magnetic structures are potentially applicable to ultrafast memory, rf oscillators and detectors. Studies on magnetic thin films containing vortex structures exhibit interesting behavior under external field and/or current bias like polarity switching, core displacement and core gyration with high frequencies inside the nanomagnet. Magnetic Force Microscopy technique allowed to observe that the antivortex pair can be rotated around the center by an external magnetic field, an important characteristic to be employed in magnetic storage. P.Tiberto@inrim.it

Within the EMRP Project "Metrology for Advanced Industrial Magnetics", theoretical and numerical models were developed for the study of magnetotransport properties of patterned magnetic films and magnetic nanowires with geometrical configuration favouring domain wall pinning, as promising candidates for magnetic field sensing applications. The attention was focused on the anisotropic magnetoresistance phenomenon, which represents the main magnetotransport contribution in nanostructures made of soft magnetic materials. Working conditions and geometries

for the design of optimized sensing elements and their integration in efficient magnetoresistive devices have been derived.

Miniaturized graphene devices for magnetic field sensing applications based on the Hall effect have been modelled, as a support to the experimental characterization performed by the "Quantum Detection" Group at NPL. In this framework, a carrier transport model was developed to interpret scanning gate microscopy images on graphene Hall bars, where a magnetically coated tip is employed to map the sensor response to localized magnetic fields. The models enables to take into account the perturbing effects induced by tip-. the investigation of edge effects in side-gated graphene nanodevices. a.manzin@inrim.it

A. Manzin, V. Nabaei, H. Corte-León, O. Kazakova, P. Krzysteczko, and H.W. Schumacher, "Modeling of Anisotropic Magnetoresistance Properties of Permalloy Nanostructures", *IEEE Trans. Magn.* 50, 7100204 (2014).

H. Corte-León, V. Nabaei, A. Manzin, J. Fletcher, P. Krzysteczko, H. W. Schumacher, and O. Kazakova, "Anisotropic magnetoresistance state space of permalloy nanowires with domain wall pinning geometry", *Scientific Reports* 4, 6045 (2014).

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R. K. Rajkumar, A. Asenjo, V. Panchal, A. Manzin, O. Iglesias-Freire, and O. Kazakova, "Magnetic scanning gate microscopy of graphene Hall devices", *J. Appl. Phys.* 115, 172606 (2014).

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