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# Progress report on electrical metrology at VTT MIKES between 2015 and 2017

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## Organizational changes

Since the beginning of 2015, MIKES (about 65 employees) has been a part of VTT Technical Research Centre of Finland Ltd (about 2500 employees), which is a fully state-owned not-for-profit-company. According to Finnish legislation, VTT is Finland's National Metrology Institute since the beginning of 2015. In practice, national metrology activities are still concentrated in MIKES. After an organizational change in VTT in the beginning of September 2016, MIKES (National Metrology Institute VTT MIKES) has been one of the five Research Areas of Knowledge Intensive Products and Services, which is one of the three Business Areas of VTT. MIKES's Electrical Metrology Team with about 20 researchers is responsible for Finland's national metrology activities in fields of electricity, time and frequency, and acoustics.

## Quantum current standard and other applications of single-electron effects

In 2015, MIKES continued work with single-electron transport in the SINIS hybrid turnstile in the framework of joint research project Qu-Ampere of the European Metrology Research Programme (EMRP). However, due to problems in sample fabrication, theoretically predicted high performance of the hybrid turnstile as a quantum current standard could not be properly demonstrated during the project which ended in April 2015. After that, MIKES concentrated on effects of cryogenic microwave background and single microwave photons on SINIS single-electron tunneling (SET) devices in EMRP project MICROPHOTON coordinated by MIKES. Methods and equipment for studies of microwave background were developed, including an RF-SET-based charge detector, a sample chamber with variable level of filtering and shielding, and on-chip filtering [21]. With that setup, MIKES in collaboration with PTB and Aalto University demonstrated that a single-electron trap excited by individual photons originating from the electromagnetic microwave background can be used to obtain spectral information of cryoelectronic devices at millimeter wave frequencies with extremely low signal levels [1]. When the microwave attenuation of an on-chip filter consisting of an array of aluminium SQUIDs was adjusted with a magnetic field, the hold time of electrons in the single-electron trap changed by two orders of magnitude. In a resistive transmission line filter made of titanium, a surprising decrease of attenuation was observed when temperature decreased below the superconducing transition temperature of titanium.

Benefitting from VTT's excellent clean-room facilities, MIKES has started a project to develop silicon-based single-electron pumps. The first devices have been designed, and their fabrication is in progress. MIKES will study those devices and other semiconducting single-electron pumps in project e-SI-Amp of the European Metrology Programme for Innovation and Research (EMPIR). For those measurements, cryogenic cabling with reduced current noise has been developed, including, e.g., vacuum-insulated cables between room temperature and the 2nd cooling stage of the pulse tube refrigerator [2]. With that cabling, noise peak below 4 fA at the 1.4 Hz operation frequency of the pulse tube and a white noise density of 0.44 fA/Hz$^{1/2}$ in the millihertz range were obtained.

We have also started activities with quantum phase slips (QPS) in superconducting nanowires (SNWs). We have fabricated the first silicide-based SNWs and made some preliminary experiments with them, but not yet with conclusive results. One of us has analyzed further his earlier experiments made with titanium SNWs in University of Jyväskylä to increase understanding of QPS phenomenon [3-5].

In addition, MIKES develops thermometry applications of single-electron tunneling in close collaboration with Aalto University. In joint research project InK of EMRP, combined standard uncertainty ($k = 1$) below 0.5% was reached in determining the thermodynamic temperature in the temperature range from 20 mK to 200 mK using the primary Coulomb blockade thermometer (CBT) [6], and agreement within measurement uncertainty was obtained in comparison with other primary cryogenic thermometers [7]. We have also demonstrated that CBT can be used up to temperature of 60 K with precision better than 1% [8].

## Applications of Josephson AC voltage standard

The development of an ultra-stable semiconductor-based arbitrary waveform generator DualDAC (commercially available from Aivon Ltd, Helsinki, Finland) was continued in EMRP projects Q-Wave and AIMQuTE. Performance measurements with an ac quantum voltmeter at PTB over the last 3,5 years have allowed improvements of the source markedly. Feedback from other institutes (INRIM, CMI, METAS, CEM and Silecian University of Technology) has also been useful. The stability of the amplitude ratio of the two channels approaches $10^{-8}$ which is very useful for fully digital impedance bridges, for example. Even for a single channel, the short-term amplitude and phase stability of the new source have been observed to be better than those of best commercial calibrators. Recently, the potential of the source to be used as transfer standard of multi-tone voltage waveforms was investigated by circulating one unit in five NMIs [22]. The preliminary results suggest that the output signal amplitudes stay in a ± 3 parts per million envelope over half a year. Even better accuracy could be anticipated by doing corrections enabled by simple DC voltage measurements at internal test points. Currently MIKES works for extending the voltage and frequency range of the source and towards further cleaning the signals. Applications could be found in various metrological experiments, like impedance bridges, ADC calibrations, thermal converter measurements etc.

MIKES started building a compact cryocooler-based Josephson impedance bridge for audio frequencies in a recently ended EMRP-project AIMQuTE. This development is based on the experience obtained in collaboration with PTB on Josephson bridges excited with square waves. Two programmable 1 V arrays provided by PTB were mounted to a pulse tube cryocooler. Unfortunately, problems of extracting dissipated heat from the Josephson junctions were found to be difficult to overcome. Hence, we started designing and building an apparatus where a He liquefier was built around the pulse tube cold head to provide liquid bath for the arrays. Once finished, we expect array performance comparable to that typical in LHe dewars. Compared to typical setups with LHe dewars we expect better performance from the bridge because of shorter connecting cables, for example. This work is planned to continue with investigations of a possibility to place a graphene based quantum Hall chip close to the Josephson arrays as a first step towards a universal quantum standard for electrical quantities.

## Resistance and graphene

QHE resistance standard has been continuously upgraded. New equipment for CCC resistance bridge was purchased from Magnicon GmbH and successfully used in QHR measurement.

We have continued research activities with epitaxial SiC graphene. Fabrication technology has been mainly developed by Aalto University [9], and knowledge of fabrication of graphene-based QHR devices was transferred successfully from Aalto University to MIKES in autumn 2016. In EMRP project GraphOhm, QHR devices fabricated in Aalto University were studied as a collaboration of MIKES, BIPM, and KRISS. In KRISS, the resistance value of SiC graphene Hall devices were tuned by chemical doping, heating, and UV irradiation at the ambient condition. In precision measurements with a CCC resistance bridge, relative deviation from $R_H(2)$ of less than 30 parts in $10^9$ was achieved at temperatures up to 6 K and magnetic field down to 7 T with driving current of 19.4 μA [23]. In BIPM, the charge carrier density $n_c$ could be reversibly varied by either treatment with UV light or using molecules from aqua ammonia [24]. After setting the optimum $n_c$ for the QHR device, accurate QHR measurements were performed, and results at $B$ = 10 T and $T$ = 1.3 K with 40 μA current showed agreement with a conventional GaAs reference at the relative level of a few parts in $10^9$.

Series connection of four quantum Hall effect (QHE) devices based on epitaxial graphene films was studied for realization of a quantum resistance standard with an up-scaled value [10]. The tested devices showed quantum Hall plateaux $R_H(2)$ at a filling factor $\nu = 2$ starting from a relatively low magnetic field (between 4 T and 5 T) when the temperature was 1.5 K. The precision measurements of quantized Hall resistance of four QHE devices connected by triple series connections and external bonding wires were done at $B$ = 7 T and $T$ = 1.5 K using a commercial precision resistance bridge with 50 μA current through the QHE device. The results showed that the deviation of the quantized Hall resistance of the series connection of four graphene-based QHE devices from the expected value of $4\times R_H(2) = 2h/e^2$ was smaller than the relative standard uncertainty of the measurement (< $1\times10^{-7}$) limited by the used resistance bridge. Epitaxial graphene based quantum Hall resistance devices with eight series-connected Hall bars have been fabricated and tested, too, but the quantized Hall resistance deviated from the expected value much more than in our earlier experiments with four series-connected Hall bars [25]. We have also developed epitaxial graphene devices for other application, especially for very sensitive gas detection [11-13].

The main role of MIKES in EMRP project GrapOhm was to develop a low-frequency current comparator (LFCC) for room-temperature operation at frequencies below 1 Hz [14,26]. The work has been done in close collaboration with PTB and BIPM. Comparative QHR measurements were performed using the developed LFCC and BIPM-CC with the modified BIPM low-frequency (0.5 Hz) ac bridge, and agreement between the two comparators at relative level of 7 parts in $10^9$ was demonstrated. We have performed experiments to determine the low-frequency to “dc” correction for LFCC, and we have found that the correction is at the level of (7-15)x$10^{-9}$ at frequencies between 0.15 Hz and 0.025 Hz. The reproducibility of the correction is limited by the $1/f$ noise of the used amplifiers and the temperature and time instabilities of the resistors. Tests of the developed LFCCs using ac bridge of BIPM and commercial electronics designed for operation with CCC demonstrated the possibility of establishment of an easier-to-run setup operated at frequencies below 0.5 Hz for resistance metrology without compromising uncertainty.

## Power and energy

MIKES has developed a multichannel sampler for the most accurate three phase power and power quality measurements. The PCB was carefully designed in order to fully utilize the good characteristics of the selected ADC converter (AD 7690, TC ±0.3 ppm/K) and voltage reference (LTZ1000, TC ±0.05 ppm/K). Blackfin evaluation kit is used to interface the ADCs with a PC. The software performs power calculations according to IEEE1459 [27].

Support for digital input and output in line with IEC 61850 has been added to the system [28]. Reservation has also been made for using a GPS module and/or Ethernet connection for time stamping the samples.

MIKES has coordinated EMRP project FutureGrid (Non-conventional sensors for future power grids), where our research contribution has concentrated on development of current measurement system based on Faraday effect in optical fiber (together with SP, LNE, TU Chalmers and University of Strathclyde), and on improvements of current measurement with Rogowski coil (together with TUBITAK, CMI, SMU and FFII). Precision measurement techniques for measurement of losses of high voltage reactors was developed in ElPow (Metrology for electrical power industry) project. An agreement of was achieved in a bilateral comparison [29]. Applicability of different types of sensor for on-site current measurement has been studied in EMRP project SmartGrid2.

## High voltage metrology

In EMRP project HVDC lasting from 2010 to 2013, MIKES was responsible for coordinating the design, manufacture, and calibration of a modular 1000 kV direct voltage divider. The design and long time stability of the module has been published in [15-17,30].

A new transient recorder has been taken into use for impulse voltage measurements. Analysis software for both lightning and switching impulse voltage measurements was updated. The new software now uses deconvolution for correction of recorder input stage response errors. As a part of EMRP project ElPow, the new system was used for characterization of megavolt impulse dividers at PTB (joint effort of PTB, MIKES, and SP). Also, a new impulse voltage divider was developed in ElPow project for nanosecond impulses up to 600 kV.

## Other research activities

In the joint research project MetNEMS of EMRP, VTT MIKES developed a sensitive MEMS-based voltage detector that has great potential e.g. as a sensitive null detector [18].

In EMRP project MESaIL, MIKES has been involved in development of an impedance stabilization network for measurements of AC-operated LED-products together with VSL and METAS. LED lamps and other solid-state lighting products (SSL) often include built-in AC/DC-converters that may cause problems when driven with programmable AC voltage sources of different types, possibly leading to different values of measured power factor, active power consumption and other parameters. MIKES has previously studied the issue in close contact with the Aalto University by developing an adjustable power line impedance emulator and carried out several measurements of commercial LED products with it connected between the programmable AC voltage source and the LED product under test to obtain effective impedance closer to real power system for the product under test. In the MESaIL project, a fixed impedance stabilization network (ISN) was developed for frequency range of 50 Hz – 2 MHz. Four operational ISNs were constructed in the project by MIKES and they are currently undergoing final measurements with different types of AC voltage sources by MIKES, VSL, and METAS, including a selected group of AC-operated LED products that were found to represent typical behaviour of such products on the market.

## Comparisons

MIKES has participated the following key or supplementary comparisons whose final or draft report appeared during the reporting period: EURAMET.EM-S33 (AC up to 200 kV), EURAMET.EM-S34 (Capacitance and dissipation factor up to 200 kV). The results of MIKES are good and support CMC claims. Results of EURAMET.EM-S37 (Current transformer calibration systems up to 10 kA) are not available yet [31]. In addition, two bilateral comparisons with PTB were performed. In 1 mH and 10 mH inductance comparison, excellent agreement in measurement results within the overall uncertainty of the comparison that varied from 14 µH/H to 62 µH/H in the frequency range 100 Hz to 2 kHz was reached [19,32]. In high voltage ac calibration system comparison, differences in measured peak and rms voltages according to IEC 60060-1:2010 were less than 50 µV/V for all measured voltage levels up to 150 kV [33]. MIKES has actively supported launching EURAMET.EM-S42 (Lightning impulse voltage up to 700 kV). MIKES measurements were performed in November 2016 at PTB.

## Publications 2015 -

### Publications in refereed journals


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#### Patents

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