Dielectric Measurements

A survey and summary

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Introduction

This is intended as a summary of some references about limitations and methods of dielectric measurement. It is mainly for background learning about work with frequencydomain measurements in the range 0.1 mHz to 100 Hz, but some general points about 'low-level measurements' have been included. Works by Jonscher that have been more thoroughly studied in the report on the dielectric response of materials have been of interest here too. A general-purpose book by Keithley Instruments was also read, as an up to date work about the features of modern measurement equipment and methods.

Synopses of the references

[Kei04] Keithley Instruments, 2004

Low Level Measurements Handbook

This book is freely available in print and on the web, from a manufacturer of sources and measurement systems for a wide range of low-level measurement. It has quite a lot of duplicated, or triplicated, content, besides some laborious derivations of elementary results, but it also has details of different types of equipment and their limitations; I'd recommend it as a skim-read to get some extra hints about choice and use of equipment.

INSTRUMENT SPECIFICATIONS.

Sensitivity smallest detectable change in signal.

Resolution smallest observable portion of signal.

Uncertainty estimate of possible error (deviation from the true¹ value).

Repeatability similarity of successive measurements in same conditions.

Reproducibility similarity of measurements in (known) different conditions.

Transfer stability similarity between two measurements within a short time, at very similar temperature, for the sake of measurements comparing an object to a known 'secondary' standard (sounds very much like repeatability).

 $^{^{1}}$ No need for quibbles about 'what is truth' and so on, here, I hope: substitute 'standard' or 'reference' or 'canonical' or something such, if really bothered.

Precision '... more qualitative ... freedom from uncertainty ... often in context of repeatability or reproducibility, ... shouldn't be used to mean accuracy.' (This goes against my background, in either science and in computing, where precision refers, highly quantitatively, to the ability of the system to convey detail [e.g. significant figures], regardless of how truly the detail represents the true measurand/result; this seems to a bit like the way 'resolution' is used here.)

Resolution the ratio of the smallest count to the maximum count, that can be displayed; for example, a $5\frac{1}{2}$ digit display can show 200 000 different values, so has a resolution of 5×10^{-6} .

Temperature deratings temperature can affect the instrument's reading. An example for 'newer' instruments is that the stated specifications are true from 18-28 °C, and that ranges outside this should have something like \pm (5 ppm of reading + 5 ppm of range) per °C outside this range, added to their uncertainty.

Time drift most electronic instruments can change over (long) times – 'time drift'; this defines a time during which the calibration is valid.

Speed of a measurement becomes more important with lower impedance measurements than those that require electrometers, as (external) circuit settling times tend to dominate the time with high impedance measurements. Measurement speed is usually stated as readings per second under given conditions.

Noise 'normal mode' noise (i.e. 'differential mode' in 'normal' terminology) is that which appears across the same terminals as the signal; this noise may for example be 50 Hz noise polluting a DC signal; the normal mode rejection ratio, NMRR, is the decibel ratio of peak normal mode noise to peak measurement deviation; the circuit should be designed to avoid normal mode noise, as this can much affect measurements. The 'common mode' noise appears together on the measurement terminals, so can more easily be avoided in the measurement; shields should be connected only to one place in the circuit, in an attempt at avoiding this noise.

Warm-up Waiting for an instrument to warm up fully is important for very sensitive measurments. This can take several hours, and is the process of getting all parts (contacts, thermoelectric effect, temperature coefficients) to the expected values. When the temperature of an instrument changes, its deviation in accuracy may overshoot the stated value then recover, due to different parts in the instrument reaching their equilibrium temperatures at different rates.

FUNDAMENTAL NOISE Johnson ('thermal') noise is $P = 4k_{\rm B}TB$ from the thermal motion of charges; metallic conductors approach this limit, and other conductors have rather higher values. The rms Johnson noise voltage in a metallic resistor is then about $V = \sqrt{4k_{\rm B}TBR}$, and the rms Johnson noise current is about $I = \sqrt{4k_{\rm B}TBR^{-1}}$. The peak-to-peak noise voltage or current (given, presumably, the Boltzmann distribution) is within 5 times the rms value for 99% of the time, and this is often used as a level for noise calculations. Reducing the measurement bandwidth will reduce noise: the bandwidth *B* of low-level (quasi-DC) instruments is about $0.35/t_{\rm rise}$ in terms of the 10-90% rise-time, or $0.314/t_{\rm int}$ in terms of integration time of an ADC, or $\pi/2$ of the upper 3 dB limit of an analogue measuring circuit i.e. B = 1/(4RC) after a bit of 2π -cancellation for the filter formed by the shunt input capacitance and the source resistance. The temperature may in some cases be usefully reduced by cooling in for example liquid nitrogen, which thanks to the square-root would reduce the noise voltage or current only by about a half compared to room temperature. Reduction of resistance is often impractical. In a voltmeter configuration, the source and internal resistances are shunted (in a small-signal sense), so the (smaller) source resistance will be dominant. In an ammeter configuration, both source and measurement resistances contribute thermal noise, but the effect of the measurement resistance is much reduced in the feedback ammeter. The Johnson noise is the value just thermal excitation, without any current. In the presence of a drift, the total noise increases, only slightly in metals, but more in metal-film resistors and even more in carbon-composition resistors.



Figure 1: Representative [lower] limits of measurement with time-response from 0.1–10 s, for an electrometer, a digital multimeter (DMM), a nanovoltmeter (nVM) and nVM with preamplifier. From [Kei04] page '1-5'.

CLASSES OF MEASUREMENT DEVICE.

The Electrometer. This is a 'highly refined DC multimeter', specialised in measuring very small currents and from high resistance sources, but some three orders of magnitude *less* able than a nanovoltmeter at measuring very small changes in voltage from relatively low resistance sources. The electrometer *voltmeter function* can cope with sources >1000 T Ω , and its input offset current is <3 fA. The electrometer *ammeter function* is limited only by theoretical limits or the input offset currents, so currents as low as 1 fA can be measured, making it suitable for measuring the output of e.g. photomultipliers and mass spectrometers. The electrometer *ohmmeter function* can be acheived by measuring voltage while feeding from a constant current source, which gives measurements up to 200 G Ω ; alternatively, avoiding the electrometer's relatively poor voltage resolution and giving the (usually) beneficial feature of a known stress on the test object, a constant voltage can be used, and the current measured by the electrometer, which permits measurements up to $10 \text{ P}\Omega$. The electrometer *coulombmeter function* is without an equivalent on DMMs: apart from actually measuring charge, this function is useful in measurement of (mean) current, avoiding the influence of internal thermal noise in the instrument; as low as 10 fC can be measured, with a low voltage burden of around $100 \,\mu\text{V}$.

Digital Multimeter, DMM. DMMs vary from very cheap handheld units to expensive high-precision units; they don't come as close to theoretical limits as electrometers do, but advances in the technology are moving the top-of-range DMMs closer (question: what distinction is there between DMM and electrometer, apart from range? is the measuring method a defining feature?). A top-quality DMM might manage limits of 10 nV, 10 pA and $1 \text{ G}\Omega$.

Nanovoltmeter, nVM. An obvious weakness of electrometers, seen in figure 1, is the measurement of small voltages with low impedance sources. An nVM is optimised for this task, having much lower voltage noise and drift, but higher current noise and drift, with input impedance similar to that of a DMM. The limit of sensitivity is about 1 pV.

Other specialised variations and combinations. Some other standard types of instruments exist for particular tasks, sometimes with the advantage of lower cost and less complexity than for example an electrometer, or sometimes with a further useful combination of features. A micro-ohmmeter deals with very small resistances, using a 4-wire method; $10 \,\mu\Omega$ is about the lower limit. A picoammeter performs the ammeter function of an electrometer, with lower price and sensitivity, sometimes higher speed, and similar voltage burden. A source-measure unit (SMU) can provide controlled voltage or current and can measure current or voltage. The current measurement is typically similar in performance to that of an electrometer. A SourceMeter (\mathbb{R} etc., so presumably just a Keithley term) adds the ability to do a bit of arithmetic to derive things like resistance; unlike a DMM it can run sweeps rather than single-point resistance measurements; being intended for 'high-speed, production test applications' it seems rather likely it's not as sensitive as the typical SMU, but this is not stated. A pre-amplifier stage placed very near the measured quantity may be used to advantage in voltage (nVM-preamp) and current (low-current preamp) measurements.

CIRCUIT DESIGN. 'Circuits used in low-level measurement instruments [can generally be] understood as operational amplifiers.' Some circuits built around op-amps are shown towards the end of section 1 of the book, for various types of instrument.

The electrometer voltmeter is a direct connection to the non-inverting input, then a feedback to the inverting input from a divider on the output. For the nanovoltmeter a similar circuit but with higher gain is suggested: the nanovoltmeter demands low noise rather than extremely low offset current and high input impedance, and this is implied to be achieved through differences in the part represented as an op-amp, rather than in fundamental changes in configuration of the circuit around the op-amp.

The shunt ammeter is a voltmeter as described above, connected across a shunt resistance: low values of shunt resistance have the advantages of reducing response-time, permitting generally more stable and accurate low-value resistors to be used, and giving less voltage-burden to the measurement circuit; their disadvantage is the reduced signal. The feedback ammeter is what we use in the dielectric spectroscopy systems (IDA200, IDAX300): the input current is matched by a current through a feedback component (here, a resistor) from the op-amp output, with the common point being the inverting input; the non-inverting input is fixed to earth potential. To get higher measurement speed, when limited by the charging of stray shunt capacitance across the feedback resistance, an extra capacitance and resistance can be added to make the circuit have a static behaviour (like trimming an oscilloscope probe, or designing a high-bandwidth HV divider!). Logarithmic picoammeters can be made by using semiconductor junctions as feedback components, with the advantage of a wide range of measurable currents within the measurable output range of the electrometer voltage, without range-switching.

The coulombmeter circuit is a feedback ammeter but with a plain capacitance instead of resistance as the feedback component. The low offset current and high input impedance of an electrometer make the Q = CV relation well approximated. The apparent input capacitance is large, for frequencies where the electrometer can respond: it is the feedback capacitance multiplied by the (large) electrometer gain.

A remote pre-amp is shown, using triaxial cable to carry a signal to an amplifier that makes it much larger, to be less affected by noise picked up during transfer to the recording system.

There are several variations on an electrometer ohmmeter. In one, a neat connection of series voltage source and resistor between the op-amp inputs (virtual zero-voltage) provides a constant current source to drive current through the measured resistor, the same op-amp being the output buffer; its output can then be used to guard the non-earth connection to the measured resistor. For low-impedance measurements (even below 100Ω , but particularly for micro-ohmmeters) the 4-wire method can be used. DMM ohmmeter functions generally compare ratios of voltages across a known internal resistance and the measured component, in a series loop.

MEASUREMENT OF HIGH-RESISTANCE SOURCES. These are measurements for which the electrometer, or associated more specific equipment such as the picoammeter, is appropriate. As an aside: the terminology of the 'HI' and 'LO' terminals into a meter seems to refer to their resistance, rather than anything to do with potential; the highestimpedance point in the test circuit should be connected to the 'HI'.

Voltage measurement has two main instrument imperfections to consider, apart from noise and calibration: input resistance is a measure of the meter's loading on the circuit, the 'current burden'; input offset current is an extra current that flows in the measurement circuit due to the meter's internal workings, possibly in either direction. The effects of both of these imperfections on the measured voltage can easily be deduced for the Thevenin equivalent source, but they are not well explained in the book: no example is given of looking at *both* of the effects together, and the idea of a constant current source on an output that could well have nothing connected is a little strange — over what range of source impedance can the current really be assumed constant? The obvious distinction between the two effects is that the offset current gives a constant voltage error, possibly of either polarity, for a given source impedance, while the input resistance gives a proportional voltage error for a given source impedance, always subtractive.

Current measurement has corresponding instrument imperfections: the series resistance carries the measured current, creating the 'voltage burden' as a series voltage in the measurement circuit; the input offset current shifts the measured value of current from the actual (terminal) value by some positive or negative constant. A feedback ammeter, with a noise source on the (supposedly earthed) non-inverting input, gets a higher consequent noise voltage on the output when the source impedance is low - consider that a greater output variation is then needed in order to drive the inverting input to match the noisy non-inverting signal. 'Most picoammeters' will have a maximum recommended value of (shunt) capacitance in the source's (series) impedance. Current measurement can also be performed by use of a feedback coulombmeter (capacitive feedback on electrometer) used to measure a mean current over some time interval. In some cases the interval is fixed, in others it may be chosen to be until a certain voltage is reached on the output. There are several advantages over a resistive feedback ammeter. The response is faster, limited by the electrometer rather than by the time-constant of feedback resistance and the capacitance that shunts this. The thermal noise of a feedback resistor is avoided, making this method preferable to a feedback ammeter when dealing in the region 1 fA; very high resistances aren't practical as components, anyway. Larger capacitances in the source can be tolerated with this method, and pulsed current can be averaged (think PD!).

Higher ranges of charge than available on the coulombmeter mode may be obtained, with many electrometers, by setting to voltage measurement and using an external capacitance as the feedback.

Readings taken at zero input may drift, with time or temperature; the zero-check can be used to make a short-term assessment of this, and zero-correct (sometimes included in zero-check) compensates the reading. The 'suppress' or 'rel' controls on some picoammeters or electrometer ammeters can be used to compensate even for external offsets. There's no use short-circuiting a feedback ammeter's input to get an idea of internal offset: with the feedback left powerless the numbers won't mean anything.

When measuring charge, note that zero-check will cause the charge to be lost!! as it connects a fairly low value resistance, some $10 M\Omega$, across the input! Do the zeroing before connecting the test object. The same is true for zero-check on other modes (at least, ammeter is mentioned) but in this case one is generally not so worried about losing some charge.

'Zero hop' is the sudden jump in reading after removing zero-check; this value should be subtracted from subsequent readings (why does it happen?).

Guarding is useful not only for reducing leakage current in DC or AC measurements, but also for improving settling time when a shunt capacitance has to charge from a highimpedance voltage source that is being measured; the gain of a buffer driving a guard screen makes the charging much quicker. Guarding may be by a buffer to maintain a screen at the potential that is being protected (typical for voltage measurement) or by reliance on the 'low' connection of an ammeter being at the same potential as its sensitive 'high' input signal that is to be protected. Shielding is the prevention of external fields, of which mainly the electro(quasi)static are considered here by a conductive enclosure; this is recommended for currents <1 nA but even above this one should check for influence of electrostatic fields by moving a statically charged object around or introducing a shield.

When measuring with high input-impedance meters, the rest of the measurement circuit can be a weak link. Leads and connectors should be ones suitable for this purpose, tested regularly in the absence of a test-object. A suitable material for insulation in the test equipment should have high volume-resistivity, high surface-resistivity, low water absorption, low dielectric absorption and low piezoelectric (charge imbalance through mechanical stress) and triboelectric (charge unbalance through friction of materials). Sapphire is the best material in these ways, but it is expensive and is hard to machine; it is used in very demanding cases for currents of fA down to aA. Quartz differs mainly in a higher piezoelectric effect. Glass and ceramics have good volume-resistivity but trouble with piezoelectric properties, surface humidity and ease of machining. Polyethene has good volume resistivity, but the surface properties are much affected by humidity; it is very well suited to use inside cables, due to its flexibility. It is commonly used in coaxial and triaxial cables, where the surface effects should unimportant as long as terminations (often teflon) have better surface properties. Teflon is the 'most satisfactory and commonly used' insulator for low-level currents >10 fA; it has good surface resistivity even with some humidity, resistance to high temperatures, flexibility and easy machining; the main trouble is piezoelectric or triboelectric effects when deformed, but these, with care, are not significant when measuring above about 100 fA.

Low-noise cables include graphite particles between the insulation and screen, to avoid triboelectric effects by lubricating movements with a material that also forms a conductive layer. Connections should not be moved or stressed during measurement. Insulators should not be touched; washing in methanol then drying for several hours, perhaps in dry nitrogen for better effect, should be done if the surface gets contaminated. Electrochemical effects can produce extra currents, for example some nA between tracks on a printed circuit board that has not been properly cleaned after etching.

LOW-RESISTANCE SOURCES. Very low voltages or resistances are often the measurand when dealing with low-resistance sources. Voltage offsets then become more important than with the typical high-resistance measurement of higher voltages. A voltmeter itself can have an internal offset, which if stable can be compensate for by shorting the input and using a zero-correct function (but see later about themoelectric effect in contacts; the shorting must be clean!). Ohmmeters can use tricks such as switching the applied voltage, to keep checking the input offset so as to subtract a recent value from the next measurement.

In the external circuit, radio frequency interference (RFI) may be coupled in from broadcast radio, contact arcing, etc., and the rectification of this by non-ohmic contacts or saturated components can add a DC or quasi-DC voltage to the circuit. Thermoelectric voltages are 'the most common' source of problems: the voltages generated across junctions of dissimilar materials depend on the temperature difference between the A/B and the B/A junction (where A and B are two different materials, and we note that to make a complete circuit there cannot be just one type of junction) and on the Seebeck coefficients of the materials. Copper-copper junctions have $<0.2 \,\mu\text{V}/^{\circ}\text{C}$ but copper-copper-oxide junctions have about $1000 \,\mu\text{V}/^{\circ}\text{C}$; copper with silicon has $400 \,\mu\text{V}/^{\circ}\text{C}$ copper with gold or silver has has $0.3 \,\mu\text{V}/^{\circ}\text{C}$ and copper with lead has $1-3 \,\mu\text{V}/^{\circ}\text{C}$.

The measured thermoelectric voltage can be reduced by reducing temperature differences, for example by proximity and strong thermal connection to good, shared thermal conductors, and by sensible choice of materials and clean junctions. Remaining effects may be removed by taking the mean of measurements made with the junctions in reversed order, so that only the desired measurand is not cancelled out.

Commonly occurring levels of magnetic field can induce significant voltage: quasistatic fields linking moving conductors can, in the case of the earth's magnetic field and a dangling conductor, induce some nV; changing fields such as power frequency and radio broadcast or other RFI can induce the voltages that add to DC offset if rectified within the measurement circuit. These effects are reduced by minmisation of loops, fastening of leads along their run, twisting of pairs or use of coaxial cables, and possible shielding by for example mu-metal or (for HF) conductive enclosure.

Earth loops allow external sources that put current through earth connections to send some of this current through the measurement circuit, adding to voltage drops, and they also provide another loop for inductive coupling: single-point earthing is desirable for measurement circuits.

Non-ohmic contacts can arise from oxide layers or other junctions of dissimilar materials. By measuring at different ohmmeter ranges one has a good chance that a different applied voltage will be used, thus showing up any gross voltage-dependence of resistance.

A 'dry-circuit' measurement is one where currents cannot exceed 100 mA and voltages cannot exceed 20 mV; this is desired for testing contact equipment such as switches, if they are to be used in a similarly low voltage and current range where oxide layers on contacts will not be broken down in normal use; breakdown of the oxide film needs about 30-100 mV.

APPLICATIONS The final full section is about particular applications. Capacitor measurements include capacitance, dielectric absorption (residual voltage / 'soak' volt-age, for what we'd know as return voltage measurement, RVM), and leakage current.

Chemical measurements include ion concentration (therefore pH values), electrode potentials and standard cells, all with high resistance and a need of not 'polarising' the electrodes (?) by significant currents.

Detectors of small events, such as Geiger-Müller detectors, photomultiplier tubes and ion beams (mass spectroscopy) all require measurement of small amounts of charge.

Measurements on superconductors provide the potential for exaggerated themoelectric problems, since different metals are frequently used in the room-temperature and cryogenic parts of the circuit, and the temperature differences can be large; apart from this, superconductors obviously require good 4-point methods.

Measurement of charge on statically charged objects can be done with a 'Faraday cup', putting the charged object within a conductive enclosure which is connected (only) through an electrometer coulombmeter to a further enclosure at electrometer earth potential; hence the charge that flows equals the charge on the object.

For measuring resistivity of materials without accurately placed contacts on welldefined samples, van der Pauw measurements use four points on an arbitrarily shaped sample, with measurements in all eight combinations of a constant current source between two terminals and a voltage measurement between the other two, using both polarities; post-processing gives a mean resistivity and indicates whether there is strong inhomogeneity in the sample.

[Jon83] A. K. JONSCHER, 1983 Dielectric relaxation in solids.

[Jon96] A. K. JONSCHER, 1996

Universal relaxation law

Chapter 10 is entitled Measurement and presentation of data, so holds most of the book's material on the subject of this review. Common functions for the applied voltage to approximate are: the sinusoid $\sin(\omega t)$, done with several values of ω and with tight filtering of the response current $I(\omega)$ to give a frequency-domain measurement; the step 1(t), usually from zero to a non-zero voltage for measurement of charging current $i_c(t)$, then back to zero voltage for measurement of discharging current $i_d(t)$; the impulse $\delta(t)$, derivative of the step, only very crudely approximated as a voltage, but quite well approximated in its effect when implemented as a charge-injection.

FREQUENCY-DOMAIN METHODS have the advantage of being very narrowband, so rejecting lots of noise, even to measuring $\tan \delta$ as low as 10^{-4} or 10^{-5} .

Classical bridge methods have worked down to about 10 Hz, or in some special cases with careful operation and adjustment of oscilloscope xy traces even to 0.1 Hz. The development and easy availability of the frequency-response analyser (FRA), apparently only one or two decades before this book, have made frequencies even down to 10^{-4} Hz or 10^{-5} Hz possible, which has been important for research in LFD (low-frequency dispersion).

The FRA principle is a correlator that mixes the measured signal with sinusoids in phase and quadrature to the applied voltage. It is possible to measure harmonics by feeding these in as the correlator reference, or to use multiple correlators for different frequencies, but this is clearly not something that can be done easily in the way we now do by digitial processing of rapidly sampled data. The extent to which the power of a noise source at frequency Ω affects a measurement of N cycles, with a FRA frequency of ω , is sinc² ($2\pi N (\omega - \Omega) / \omega$), which emphasises the virtue of using a large number of cycles to shrink the window of frequencies that influence the measurement.

FRAs have input impedance in the order of $1 \text{ M}\Omega$, which requires the use of a sensitive amplifier to match it to the typical sample of $10^{13} \Omega$. The amplifier's flatness of gain and low phase-shift are important: the input current may vary by as much as 10 orders of magnitude, and one typically includes a similar range of R and C feedback components around a sensitive electrometer, to adjust the amplifier to the object and frequency. The capacitive components are low-loss capacitors with a $Z \approx (i\omega C)^{-1}$ behaviour. The highvalue resistors have a parasitic capacitance that is a significant limiting factor. A wellknown reference capacitor can be used as the test-object prior to the real measurement, to get an idea of the error introduced by the amplifier's phase-shifts.

A lower limit to test-object conductance is about 10^{-13} S, due to leakage currents and the limiting current of the amplifier. A limit on the relative sizes of the real and imaginary components of current is about $10^{-4} < \tan \delta < 10^3$, imposed by the high relative error that occurs in the small component of current due to slight errors in phasemeasurement of the current. This has a practical significance that at very low frequencies the measurement of the very small capacitive current may become inaccurate, giving rise to a change in capacitance that looks like LFD.

A measurement typically steps through frequencies with 2 points per decade while getting an idea of the specimen, then with 4 to 6 points per decade for a proper measurement. At each frequency, multiple results are taken and 'integrated' until there is sufficient convergence or a time-limit is exceeded.

FRA measurements use the FRA output of up to some 10 V, sufficient for stressing thin samples, but higher voltages are not practicable; the maximum frequency is as high as 10^7 Hz on some FRAs, but the external circuit's inidealities tend to limit the practical maximum to a lower value.

The main disadvantages in the frequency-domain are the measurement time and the detection of non-linearity. A long time is needed for measurements at several lowfrequency points; on the other hand, the worse noise-rejection of the time-domain methods can make averaging necessary for these, making the comparison less unfavourable. A time-domain measurement allows simple comparison of results for different applied voltages, while conventional frequency-domain measurements (then) records just fundamentalfrequency components, therefore hiding a lot of the detail of a non-linear response.

TIME-DOMAIN METHODS measure the response to (usually) a step function; measurement at all times $T_1 < t < T_2$ gives theoretically the frequency-domain values $2\pi/T_2 < \omega < 2\pi/T_1$ (although the presence of non-linearity, conductance and noise make the two methods differ). Repetition of a measurement for averaging may be needed for improvement of the SNR.

It is usual to measure the charging and discharging (polarisation and depolarision) currents, and to try to use these to extract a d.c. term, on the assumption that the current consists of a constant value proportional to applied voltage, and a reversible polarisation mechanism described by the dielectric response function f(t). In fact, a 'very general feature' of such $i_c i_d$ measurements is that $i_c \neq i_d + \text{const}$, and therefore $i_c - i_d \neq f(t)$.

The amplifier must follow the signal that falls through many decades of amplitude. A logarithmic amplifier can be formed by using a transistor as the feedback component, using its exponential current/voltage relation. A differential connection of two such amplifiers, to give an output proportional to the ratio of the logs of the measured and reference currents, is desirable in order to allow range-shifting and cancel some of the likely temperature-dependence.

The voltage source for a time-domain measurement must have internal resistance R such that the test object's prompt response C_{∞} is charged well before the first measured time: $RC_{\infty} \ll t_1$; it must also have low ripple, so as not to introduce noise that will disturb the low sample-current after long times. The switch must be bounce-free, and very high off-state resistance to prevent currents before turn-on and while discharging. The response time and time-base are crucial, as the correct relative times of the early samples are heavily dependent on this: bear in mind that when plotting in $\log(t)$ a constant additive error in time t due to errors in turn-on will lead to a change in shape of the curve at small times, rather than just a shift as would be so for a linear scale (not to mention effects on transforms one might want to perform).

For up to hundreds of volts a mercury-wetted relay can achieve bounce-free lowresistance contact and practically infinite off-state resistance; a disadvantage is the unpredictable delay of about 1 ms between activating the coil and getting the switching action, which necessitates driving the time-base from the relay's output rather than its coil supply. Field-effect transistors are much faster, well below 1 μ s, but have voltage limits to 15 V and an appreciable off-state current of some 1 pA; a combination of the relay and FET can take the better features of each. (Surely a FET is now much better than this?)

There have been attempts to capture time-domain data more efficiently, for example by superposition of applied signals, but (it is warned) '...in view of the superposition principle and the resulting "memory" present in the system, there is no way of shortening the time of collection of data by whatever "clever" superposition of signals ...'.

PRESENTATION OF DATA The data should span enough range of frequency or time that the nature of the response can be seen; sometimes, limitations of instruments restrict the range to less than four orders of magnitude (desired in the previous section of the chapter), but temperature shift might then help to extend the range.

The plotting method should show clearly whether the results follow an expected function: plot log-log when expecting the universal response, not semilog as though expecting an exponential. The wide dynamic range of both axes should make this requirement clear. Only the logarithmic scale of ordinate axis preserves the shape of curves when performing normalisations, for example for temperature. The logarithmic scale also shows the constant-ratio relation of the real and imaginary components. Nevertheless, it is common to see plots using linear or mixed linear (ξ') and logarithmic (ξ'') scales.

To avoid clutter of the dynamic polarisation phenomena with the d.c. current or prompt response ε_{∞} , the Kramers-Kronig relations can be used both ways on the measured capacitance and loss. There's no point trying to normalise (for example for varied temperature) variables that are functions with a significant term beyond the normalisable relation: in particular, C_{∞} must be removed; the ξ' and ξ'' components have to be treated together.

Impedance and admittance plots (Z and Y) are complex plots of respectively a series or parallel RC circuit representing the measured response, the R and C values being variables parameterised by time or frequency. An advantage is that this can sometimes make multiple parallel or series processes with different time-constants be very distinct; a disadvantage is that important ranges of data may get shrunk into small end-regions of this linearly scaled type of plot.

The 'modulus' is the reciprocal of permittivity, a relation of E to a given D rather than the other way around. Its main virtue is where the D field is largely the 'set' parameter, such as in some cases of surface or space-charge; it's not clear that this representation really helps.

On op-amps

An op-amp, the general family of the electrometer [my inference!], requires a certain minimum input current. This value may differ between the inverting and non-inverting inputs. The quoted *input bias current* is the mean of the two inputs' bias currents, and the quoted *input offset current* is the absolute difference [Sed91]. Op-amps based on BJTs may have values of, respectively, 100 nA and 10 nA, but those based on FETs have much lower values, in the order of picoamps. A popular method for reducing the d.c. output-level created by input offset is to include a series resistor in the earth-connection of the non-inverting input (in the classic case of the inverting amplifier). This has 'from a signal point of view ... a negligible effect', (but we should remember our need for very precise phase).

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