

Mineral conductivity measurements



G. Genn*, R. Morrison

University of Queensland, SMI, JKMR, Brisbane, QLD 4068, Australia

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ABSTRACT

Unlike insulating minerals, such as quartz or feldspar, the propensity of conductive minerals to heat using radiofrequency energy has not been particularly well quantified or documented in scholarly literature. A detailed knowledge of the RF properties of all minerals is required for RF energy to be effectively used in many potential applications. Electrical conductivity measurements were performed on selected sulphide minerals and magnetite between 100 kHz and 10 MHz using thin-film electrodes. However, reproducible measurements are challenging due both the high conductivity and semiconducting nature of the minerals. These measurements show variation between deposits and allude to favourable differences difference between minerals at radiofrequencies.

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1. Introduction

Dielectric properties describe how a medium interacts with, and absorbs energy from, a varying electric field. Along with the corresponding magnetic properties, these fundamental properties can be used to describe any electromagnetic interaction. Electromagnetic interactions are widely used and investigated as the basis for separation of mineral phases and include: electrostatic separation (Dance and Morrison, 1992); magnetic separation (Svoboda and Fujita, 2003); dielectrophoresis (Ballantyne and Holtham, 2010; Hatfield, 1924; Pohl, 1951); sorting based on microwave excitation and thermal imaging (Morrison, 2010; van Weert and Kondos, 2007; van Weert et al., 2009; Wotruba and Riedel, 2006); and metal detectors (Bamber, 2008). These mineral separation processes are predicated on the gangue and valuable mineral phases having different electromagnetic properties.

When an electric field is applied to a medium, the charge carriers within the medium attempt to move or re-orientate themselves with respect to the field and form dipole moments. This polarizes the medium and there are a number of mechanisms by which that occurs, such as: ionic conduction, dipolar relaxation, atomic polarization or electronic polarization. These polarization mechanisms characteristically occur in different frequency regimes and as a consequence the dielectric properties of a medium will vary with frequency.

The focus of this research was to determine relative electrical conductivities of selected sulphide minerals and magnetite in the frequency range 100 kHz to 10 MHz. To this end, specimens of

bornite, chalcocite, chalcopyrite, magnetite, pyrite and pyrrhotite were sourced from multiple locations to gain an insight into the variability of their conductivity.

The combination of dielectric test fixture and LCR (Inductance (L), capacitance and resistance) meter allow the measurement of voltage across, and the current through a Material Under Test (MUT) as well as the phase difference between them. Electrical properties (such as capacitance, inductance, conductance and absolute impedance) are then calculated within the LCR meter based on this voltage, current and phase information. A simplified electrical diagram of the test fixture and LCR meter is shown in Fig. 1.

The values output by the LCR meter do not account for the thickness of the sample or the area of the electrodes. The parallel plate model, Eq. (1), can be used to calculate the permittivity of the sample from measured capacitance and the sample and electrode dimensions. In Eq. (1); ϵ is the absolute permittivity of the Material Under Test (MUT), ϵ_0 is the permittivity of free-space, ϵ_r is the relative permittivity of the MUT, C_p is the equivalent parallel capacitance, t is the sample thickness and A is the area of the electrode.

$$\epsilon = \epsilon_0 \epsilon_r = \frac{t}{A} C_p \quad (1)$$

The loss factor of a material may also be expressed as the conductivity, σ , as per Eq. (3), and is a good measure of relative heating propensity. Conductivity is calculated from conductance G using Eq. (2).

$$\sigma = \frac{Gt}{A} \quad (2)$$

$$\epsilon'' = \frac{\sigma}{2\pi f \epsilon_0} \quad (3)$$

* Corresponding author. Tel.: +61 733655831.

E-mail address: g.genn@uq.edu.au (G. Genn).

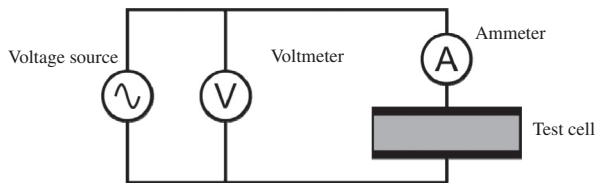


Fig. 1. Simple capacitance-cell measurement.

2. Materials and methods

Low- and radio-frequency conductance measurements were performed using a commercially available Agilent 4285A precision LCR meter and Agilent 16451B dielectric test fixture. These measurements were conducted on discs cut from solid mineral specimens using first rigid electrodes and then thin-film electrodes on the dielectric test fixture. For both the rigid and thin-film electrodes measurements were conducted using both guarded and unguarded electrode configurations.

2.1. Electrode configurations

The rigid electrodes are a set of parallel plate electrodes that are attached to the dielectric test fixture and make direct contact with the material under test. This electrode configuration has the advantage of a known electrode area but can mean poor electrical contact with non-parallel samples. Furthermore, this configuration of electrodes does not permit measurements with an unguarded centre electrode.

Thin-film electrodes guarantee good electrical contact with the sample and remove the requirement for high-precision machining at the cost of measurement uncertainty. Thin-film electrodes are created by applying a silver loaded, electrically conductive paint (RS components item code: 186-3600) to the samples. Acetate stencils were used to create the concentric circles of the centre (10 mm outer diameter) and guard electrodes (14 mm inner diameter). The dielectric test fixture allows both guarded and unguarded measurements when using thin-film electrodes by virtue of a spring loaded centre electrode; this means the outer electrodes can be retracted while the centre electrode maintains contact with the centre thin-film electrode as shown in Fig. 2.

A potential limitation of this measurement technique is due to the electrical design of the guard electrodes and the high conductivity samples. According to the electrical diagram (Fig. 3) of the dielectric test fixture manual (Agilent, 2000), the guard electrode is earthed. For comparison, Bussey includes the use of a Wagner earthing bridge for similar three-terminal capacitance-cell measurements (Bussey, 1967). In the case of highly conductive samples, such as sulphide minerals, it is possible that the guarded electrode would preferentially short to the guard electrode.

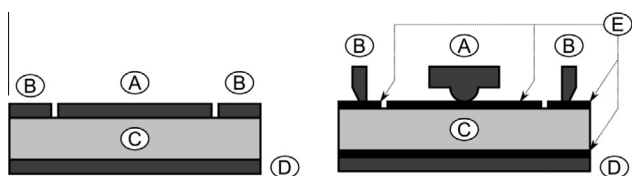


Fig. 2. Cross-section of the guarded rigid plate electrodes (right) and guarded thin-film electrodes (left). In this figure the components represented include: the guarded (centre) electrode (A), guard electrode (B), Material Under Test (MUT) (C), unguarded electrode (D), and thin-film electrode (E).

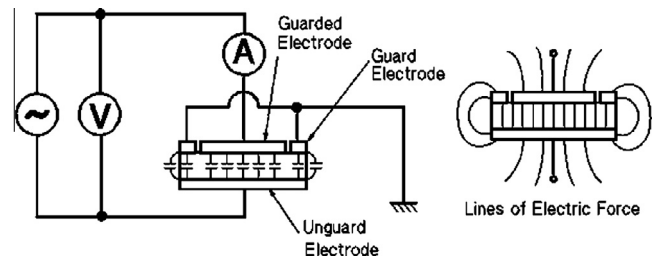


Fig. 3. Implementation of guard electrodes in the RF test apparatus (Agilent, 2000).

2.2. Calibration

Calibration of the LCR meter and dielectric test fixture for rigid plate and thin-film electrode measurements was accomplished using the automatic calibration routines of the LCR meter (Agilent, 2001). These routines measure capacitance and conductance of the cell for open, short and load circuit configurations at pre-set frequencies. Interpolation between calibration measurements is then used for measurements at other frequencies. A 1-2-5 series of frequencies was chosen to cover the two decades between 100 kHz and 10 MHz. These seven spot frequencies fully utilize the LCR meter maximum of seven user-specified calibration frequencies and means that no interpolated calibrations are used. While only a visual inspection of parallelism was required for the thin-film electrode measurements, the rigid plate electrode measurements required precise calibration of electrode parallelism in addition to the automatic calibration routines.

2.3. Measurement

After calibration, the conductivity of prepared mineral samples was measured using LCR Meter and dielectric test fixture with either rigid- and thin-film electrodes. Mineral conductance was recorded from the LCR meter at each measurement frequency along with electrode spacing on the test fixture. The procedures for measuring RF properties with the rigid- and thin-film electrode configurations are identical and are detailed in the RF test fixture manual (Agilent, 2000).

Guarded rigid electrode measurements were made at several random points on both sides of the mineral samples. Thin-film measurements were only made after all rigid electrode measurements had been completed as the thin-films can be difficult to remove. Furthermore, the thin-film electrodes are fixed on the sample surface so multiple measurements at random locations are not possible. Unguarded thin-film conductance measurements were performed with the guard electrode at 0.15 mm and 0.5 mm above the sample surface and with visual checks to ensure the guard electrode did not come into contact with the sample.

2.4. Mineral specimens and sample preparation

A total of six different mineral species were selected for RF conductivity measurement. Multiple samples of each mineral species from different countries of origin were selected to represent a range of conductivities. The specimens selected and then sourced from mineral dealers are listed in Table 1. Since the samples were sourced from collections of natural minerals there were numerous imperfections and inclusions. Additionally, specimens were identified by their surface mineralization; hence the true sample composition may not be representative of the mineral classification.

The minerals selected for investigation are generally considered to be either good conductors or semiconductors. Variation in chemical composition of semiconductors (either as a deviation

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