Fabricated Teflon Capacitors for NMR Probes

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ABSTRACT
Nuclear magnetic resonance, or NMR, probes are used to analyze membrane proteins. The configurations of the probe circuitry are based on resonant RLC circuits. These circuits are operated at microwave frequencies. A phenomenon that occurs occasionally while conducting pulse NMR experiments is acoustic ringing. In the experiments conducted at the National High Magnetic Field Laboratory, the belief is that the acoustic ringing is caused solely by the ceramic capacitors used in the circuit. Acoustic ringing can skew the data that is collected or make it difficult to read. Teflon (Polytetrafluoroethylene or PTFE) capacitors were made as an attempt to eliminate the ringing. The flat-shaped design of the Teflon capacitors also helps to relieve the space taken up from the traditional ceramic capacitors used in the NMR probes.

INTRODUCTION

Acoustic capacitor ringing is an effect that has been observed in nuclear magnetic resonance applications. This acoustic ringing makes it difficult for researchers to get accurate data from NMR spectroscopy.

Nuclear magnetic resonance spectroscopy is the use of the NMR phenomenon to study physical, chemical, and biological properties of matter of solid and liquid samples [3]. The samples are placed inside a coil included in the probe circuitry that creates an oscillating magnetic field when it encounters a radio frequency pulse. The probe is then inserted into a superconducting magnet that induces a second, static magnetic field, which is necessary for nuclear magnetic resonance. These two magnetic fields allow the atoms inside the sample to be aligned so they can be studied more carefully.

The researchers obtain data by running radio frequency pulses through the probe and an attached computer program produces a spectrum that can be interpreted by the researchers. In order to observe the signals being sent back from the probe, the system must have a quick recovery (only a few microseconds) after it is pulsed. In many instances, a ringing is observed right after the pulse, and it spans for several microseconds [1]. This ringing masks the signal being sent back from the probe and makes the spectra difficult to interpret.

CAPACITOR RINGING THEORY

Some scientists in the NMR field believe that this ringing effect is caused by ceramic capacitors within the probe circuitry. More specifically, most experts in the field agree that piezoelectric effects in the ceramic crystal lattice, along with Lorentz forces produced by

eddy currents in the magnetic field, are the source of the ringing phenomenon.

The term *piezoelectric effect* is defined as the generation of an electric potential as a result of applying pressure or mechanically altering the structure of a crystal. This effect also refers to the reverse scenario: when an electric potential is created across an asymmetric crystal, deformation of the crystal is observed. The piezoelectric effect can be seen in non-symmetric crystal structures, including quartz and many ceramics used in capacitor dielectrics. Jaques and Pierre Curie discovered this effect in 1880 [2].

The Lorentz force is only observed with the presence of a static magnetic field. The force depends on an eddy current produced by the coil, the strength of the static magnetic field, and the number of electrons per unit volume of a specific material. The eddy currents are produced when the oscillating magnetic field produced by the coil penetrates the metal probe encasement. A magnetic field produces potential differences in a conductor when passing through it, which causes these eddy currents. These currents travel in circular motions on the surface of the probe wall. The reason that a static magnetic field must be present for ringing to occur is that the Lorentz force must be present for ringing to be seen, and with zero static magnetic field strength, there is no Lorentz force, or only a very small one from the earth's magnetic field.

Polytetrafluoroethylene, PTFE for short, but better known as Teflon, was chosen as the substrate because it contains no piezoelectric properties. The structure of Teflon merely consists of two fluorine atoms that are bonded to a carbon atom as the diagram shows below in Figure 1 [4].

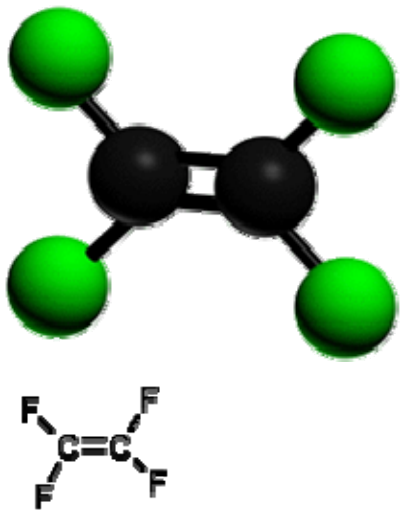

Figure 1. Atomic structure of PTFE

Since the structure has a center symmetry, it exhibits no piezoelectric effects. Without these effects in the capacitors, no ringing will be produced by the capacitors when the probes are placed in the high magnetic fields. The tests conducted at the National High Magnetic Field Laboratory to determine how the ringing occurs have been conducted using ATC ceramic capacitors in the probe circuitry using a 400 MHz magnet. Several different approaches were tried to understand this mystery.

The time length of the pulses was varied, but no change in the ringing was observed. The transceiver frequency was varied, and no relation of transceiver frequency to the effects of ringing was concluded. The coil connections were also altered several times to make them more rigid, and no change in ringing followed. The values of the variable capacitors in the circuit were changed, but no change in the ringing was seen. One of the ceramic capacitors was also shorted out and the ringing greatly reduced, but the ringing was still present due to the other ceramic capacitors remaining in the circuit. A ceramic chip

capacitor was replaced with an open coaxial line and the ringing reduced. The ceramic capacitors were removed from the proton channel and the ringing was reduced further. The biggest change in ringing that was observed was when the probe was removed from the magnet. The amplitude, but not the frequency, of the ringing depends on the strength of the magnetic field. This was concluded from data collected at different positions as the probe was removed from the magnet, as shown in Figure 2. The acoustic ringing was completely eliminated when the probe was removed entirely from the magnet, supporting the theory that Lorentz forces must be present to see ringing.

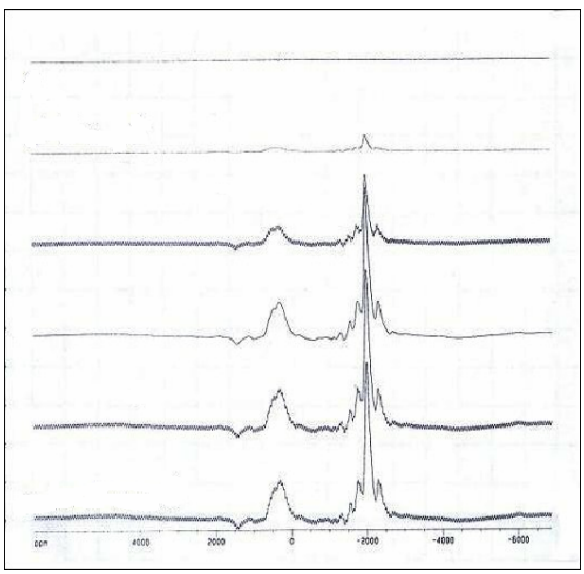

Figure 2. Spectra of ringdown as the probe is being removed from the magnet in successions. The bottom spectrum is the probe fully placed inside the magnet. The top spectrum is the probe fully removed from the magnet.

After these experiments, the consensus was that the problem involved only the ceramic chip capacitors with the static magnetic field present. The decision was then made to attempt making capacitors that would not ring in a magnetic field at microwave frequencies. This type of capacitor is currently available from industries in values of 12 pF and above, but smaller values are often preferred in microwave applications.

CAPACITOR DESIGN AND DEVELOPMENT

The material that was used to construct the capacitors was called CuFlon, a microwave substrate developed by Polyflon. The substrate was constructed with a layer of PTFE that had a sheet of copper attached on each side. Teflon was used because of its low dissipation factor, low dielectric constant, and high thermal resistance. Over the years, Teflon has been used in many applications ranging from low frequencies to microwave frequencies. It is also known that ringing has never been observed in Teflon capacitors. The Teflon in the particular sheet of CuFlon that was used has a dielectric constant of 2.1 and a dielectric strength of 2000 V/mil for one to five mils and 1000 V/mil for ten to twenty mils.

The first step in the design process was to calculate the size of CuFlon plates needed for the desired capacitor values. The equation for capacitance is:

$$C = \frac{K\varepsilon_o A}{d} \qquad (1)$$

where K is the dielectric constant, ε_o is the constant for the permittivity of free space, which was taken as 8.8542 x 10^{-12} F/m, A is the area of the copper plate, and d is the distance between the two copper plates.

The capacitance values used were the normal values in geometric progression currently available on the market in ceramic chip capacitors. The values used were: 1 pF, 1.2 pF, 1.5 pF, 1.8 pF, 2.2 pF, 2.7 pF, 3.3 pF, 3.9 pF, 4.7 pF, 5.6 pF, 6.8 pF, 8.2 pF, and 10 pF.

One concern that needed to be addressed while making the capacitors was the possibility of arcing. Arcing is the phenomenon that occurs when a dielectric can withstand no more potential difference, and current jumps through it. Arcing makes capacitors obsolete and useless because they no longer store charge when this occurs.

The problem is not with Teflon, which can withstand more voltage than it is exposed to in typical microwave frequency applications. The problem occurs with humid air, which can stand much less potential difference before arcing occurs. To solve this problem, a Teflon overhang was designed.

Figure 3. Arcing in a capacitor

The maximum voltage that the CuFlon could withstand before arcing, not accounting for arcing through the air, was calculated using the following formula:

$$V_{arcing} = \vartheta * d \qquad (2)$$

where ϑ is the dielectric strength of the Teflon and d is the distance between the two copper plates.

From this formula, the maximum voltage was 6.5 kV. With this known, the same equation could be applied to the air, which was assumed to have a dielectric strength of 30 V/mil in its most humid state. The goal was to match the breakdown voltage (V_{arcing}) of the Teflon to the breakdown voltage of air. To do this, the current path through the air must be made a longer distance to account for the large difference in dielectric strengths. A Teflon overhang was designed to add this extra distance to the path that the current must take through the air. This can be seen in Figure 4.

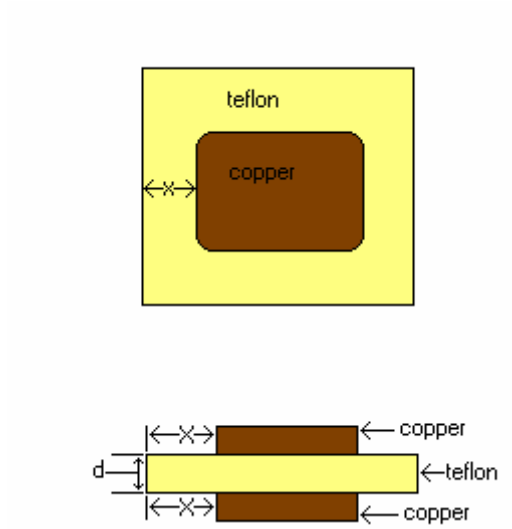

Figure 4. The top diagram shows the top and bottom view of the capacitor. The bottom diagram shows the side view of the capacitor.

The breakdown voltage of Teflon, 6.5 kV, can be equated to the breakdown voltage of air in this modified equation:

$$V_{arcing} = \vartheta_{air} * (2x + d) \quad (3)$$

where x represents the distance that the Teflon overhang must extend from the copper and d is the distance between the two copper plates. Now x can be easily solved for to complete the design of the capacitors.

RESULTS OF TESTING

Once the capacitors were made, they were tested for certain attributes. Due to the low sensitivity of the capacitor meter that was available, another process was used the measure the value of the capacitor. By soldering an inductor of a known value across the capacitor, a basic LC tank circuit was made. The resonant frequency was measured by way of a vector network analyzer. The value of the capacitor was calculated using the following relationship:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

where f_r is the resonant frequency, L is the known inductance value, and C is the unknown capacitance value. By solving for C, the formula is:

$$C = \frac{1}{4\pi^2 f_r^{\,2} L} \quad (5)$$

After this test, the capacitance values were seen to be accurate.

The next attribute tested was the breakdown voltage. This test was conducted using a variable voltage source that could produce up to 5 kV DC. The 5 kV variable voltage source had to be used due to the unavailability of a source that could produce 6.5 kV. The capacitors were connected to the source, and the voltage was increased slowly to 5 kV. No current was passed through the simple circuit, proving that the breakdown voltage was at least 5 kV. These results were expected.

It was also decided to test a capacitor with no Teflon overhang design to see what a difference the overhang made. Arcing was observed through the air at only 500 V. This proved that the Teflon overhang design was useful.

DISCUSSION

From the tests conducted, the Teflon capacitors seem to be a superior alternative to the previous ceramic capacitors that have been used in the NMR probes. The results of the tests show that the Teflon capacitors exhibit the fundamental properties of the ceramic capacitors they replaced, while eliminating the ringing problem.

Another advantage of the Teflon capacitors over the industrially available ceramic capacitors is their flat design. Because these custom capacitors are so flat, they can be inserted almost anywhere in a probe. One of the limitations that probe designers must deal with is the limited space available for probe circuitry. These capacitors can help to solve space issues because they can be directly soldered to any circuit element and can also be stacked to change the capacitance values while occupying little additional space.

Although the Teflon capacitors have not been tested in a probe, plans are being made to use them in the next probe developed. The capacitors are not expected to ring, due to the fact that they cannot exhibit a piezoelectric effect.

They should prove to be very useful in space conservation as well.

Plans are being made for future tests to pinpoint the cause of capacitor ringing. Although it is commonly believed that piezoelectric effects and Lorentz forces cause ringing, no one is sure how these forces cause the ringing. Further tests will be conducted upon completion of a test probe that will ring.

REFERENCES

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