Gigahertz bandwidth ultrahigh vacuum 50 Ω coaxial high-voltage coupling capacitor for photoelectron spectroscopy

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A bakeable (200 °C) ultrahigh vacuum 50 Ω coaxial coupling capacitor is described. The capacitor is compatible with the General Radio G874 coaxial standard, has a large capacitance (6 nF) allowing for efficient transmission of both fast pulses and long analog waveforms, can hold off dc voltages of up to 5 kV, and has a bandwidth greater than 2 GHz, allowing coupling of very fast rise-time signals from cathode ground microchannel-plate detectors, often used in photoelectron spectroscopy. The capacitor design also provides a convenient bias tee for applying high voltage to the detector anode. [S0034-6748(96)02904-9]

I. INTRODUCTION

Modern microchannel-plate (MCP) photodetectors are capable of producing subnanosecond risetime pulses,[1] allowing for (∼20) picosecond timing of light emission when using the time-correlated single-photon counting technique[2] combined with optimized amplification[3] and constant-fraction discrimination circuits.[4] Time-of-flight photoelectron spectroscopy is another technique which requires high accuracy timing, the timing resolution being directly related to the electron energy resolution. A time-correlated single-photoelectron counting technique has been implemented, for example, in studies of two-photon photoemission from metal surfaces.[5]

In photoelectron spectroscopy and in other methods requiring the detection of single negatively charged particles, it is often either convenient or necessary to bias the MCP such that the anode is floated at a high positive voltage (cathode ground operation). This implies that the amplified fast electron pulse is formed at a high dc potential, requiring a decoupling of the MCP anode from the sensitive timing electronics which follow.[6] In order to preserve the inherent high time resolution of the MCP response, however, any such decoupling scheme must meet or exceed the bandwidth of the detector. Ultrahigh vacuum coupling capacitors with small values of capacitance (several hundred pF) have been constructed by introducing a small gap in the inner conductor of the signal output cable.[6] In this work, we describe a bakeable, ultrahigh vacuum (UHV)-compatible high bandwidth (2 GHz) coupling capacitor with large dc hold-off (5 kV), which has the particular feature of high capacitance (6 nF). The device also plugs conveniently onto the output of commercially available MCP detectors and provides a bias tee for the anode.

The UHV coupling capacitor described below is used with a MCP photoelectron detector in our gas phase dynamics experiments studied by femtosecond time-resolved pump-probe photoelectron spectroscopy[7] and has been in continuous use for two years.

II. GENERAL CONSIDERATIONS

In order to preserve the fast electron pulse from the MCP, the pulse must propagate from the detector (which is in ultrahigh vacuum) to the timing electronics along a 50 Ω coaxial microwave transmission line. Therefore, any coupling capacitor must appear as a coaxial element of this 50 Ω transmission line. We note that commercially available coaxial 50 Ω coupling capacitors based upon an in-series disk capacitor do exist and conform to the General Radio G874 coaxial standard (e.g., Gilbert Engineering, P.O. Box 23189, Phoenix, Arizona 85063, Part No. 0874-9596). Unfortunately, these components are neither UHV compatible nor can they hold off a dc voltage of greater than 500 V (due to dielectric breakdown). Some commercial tapered anode microchannel-plate detectors (e.g., Galileo Electro-Optics FTD 2003) use the G874 standard for the signal output connector. Below, we present a G874-based high-frequency coupling capacitor which is completely UHV compatible, bakeable (to 200 °C) and can hold off greater than 5 kV. This coupling capacitor simply plugs onto the back of commercially available MCP detectors and, furthermore, very conveniently provides the high-voltage bias to the anode.

The dielectric (ceramic) material used for the disk is usually chosen for its high dielectric constant so that the in-series coupling capacitor may be made as small and as thin as possible. For our application (detection of both single events and analog waveforms), we require a disk material with a high dielectric constant (e.g., $K=10\,000$ for an optimized $BaTiO_3$ composite) in order to achieve efficient coupling. Unfortunately, there is often an inverse relationship between dielectric strength and dielectric constant. Typical dielectric strengths for $BaTiO_3$ composites are on the order of 50–100 V/mil. Hence, the first issue we must address is the high-voltage breakdown of the dielectric composite. We consider a disk capacitor in series with the inner conductor (signal) of a coaxial line connected to a MCP. In order to achieve high gain, the MCP detector must be operated at high voltage. In cathode ground operation, the anode floats at several kV and therefore it is essential that the disk withstand dielectric breakdown. The easiest way to achieve this is to make the disk thicker, so that it can hold off several kilovolts. However, by making the disk thicker, we reduce the capacitance and, in order to regain it, we must increase the diameter (area) of the disk. Any significant increase in the

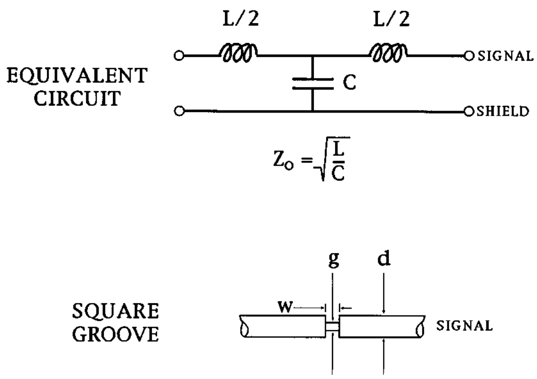

FIG. 1. Top. Equivalent circuit for the coupling capacitor. The capacitance ''C'' represents the shunt capacitance between the disk and the shield (outer conductor). Inductance ($L/2$) is added to regain 50 Ω impedance, by making a square groove in the inner conductor. Bottom. A square groove of width ''w'' is machined in the inner conductor (signal line). The diameter of the conductor is ''d'' and the reduced diameter at the groove is ''g''. The reduced diameter makes a local high impedance which acts as a series inductance, $L/2$.

diameter of the disk will introduce a new (shunt) capacitance between the disk and the outer conductor (shield) of the coaxial line. This effect is illustrated by the equivalent circuit in Fig. 1 (top), where the oversize disk has introduced shunt capacitance, labeled ''C,'' between the signal (upper) and shield (lower) conductors. This shunt capacitance especially alters the high-frequency dynamic impedance, $Z_0 = \sqrt{(L/C)}$, of the device such that it is less than 50 Ω in the region close to the capacitor. The central problem is therefore to restore the dynamic impedance of the coupling capacitor back to 50 Ω. The local dynamic impedance depends on the ratio of the local inductance to capacitance. In order to bring Z_0 back to 50 Ω, we must therefore increase the inductance in the region close to the capacitor. This can be achieved with a square groove in the inner conductor. As the inductance depends logarithmically on the ratio of the diameters of the conductors,[8] locally reducing the diameter of the inner conductor (i.e., machining a groove), as shown in Fig. 1 (bottom), yields a local high impedance which is equivalent to a series inductance: $L \propto w \ln(d/g)$, where w is the width of the groove of diameter g and d is the diameter of the inner conductor. By machining two small grooves in the inner conductor symmetrically about (and close to) the disk capacitor, we add series inductance such that the local equivalent circuit appears as in Fig. 1 (top). The width w of the grooves can easily be adjusted until the dynamic impedance is measured to be exactly 50 Ω.

III. CONSTRUCTION

We now discuss the fabrication of the coupling capacitor, with reference to Fig. 2. The G874 standard was adopted for the connectors (hermaphrodite, quick connect), the inner conductor (0.24425″ o.d.) and the outer conductor (0.5625″ i.d.). In Fig. 2, the inner connector (1) is shown. The outer connector, omitted for clarity, is a standard 874 connector and mates with item (2). The vespel feedthroughs (2) support the inner connector/conductor. Vespel (polyimide, Dupont) is a machinable, bakeable UHV-compatible polymer with

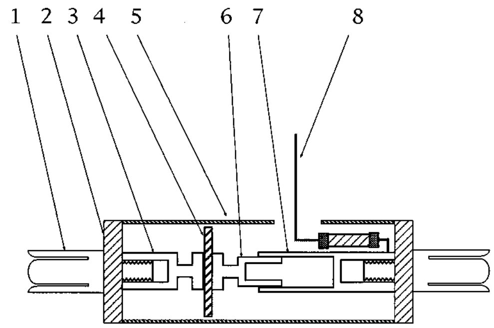

FIG. 2. A schematic of the coupling capacitor. (1) GR signal connector, (2) vespel flange, (3) signal (inner) conductor with groove, (4) $BaTiO_3$ composite disk capacitor, (5) outer conductor, (6) inner conductor with groove, (7) spring loaded conductor, (8) blocking bias resistor.

excellent dielectric strength. The outer conductor (5) and inner conductor (3), (6), (7) are also shown. The ceramic disk capacitor (4) is discussed in detail below. Although considerably reducing the bandwidth, an UHV compatible 1 MΩ blocking resistor (Dale, type HVW) very conveniently provides the high-voltage bias for the MCP anode and is shown as (8).

The (inner and outer) connectors and outer conductor were adapted from existing G874 components. The standard phosphor bronze retaining rings for the outer connector were replaced with retaining rings fabricated from CuBe. The outer conductor has a 0.125″ clear hole drilled off-center in order to bring in the high-voltage bias line. These G874 components are made of alloy plated, hardened brass, and are not UHV compatible. In order to make them UHV compatible, all G874 connectors (inner and outer) and the modified outer conductor (5) were degreased and stripped in an acid bath. The clean brass parts were first Ni electroplated (for example, ANSI QQN290, 50–100 μ-in.) and then hard Au electroplated (for example, MIL 645204, 30–50 μ-in., min 80 knoop hardness).

A pressed and fired $BaTiO_3$ composite disk (0.545″ o.d., 0.066″ thick) with very high dielectric constant (K=11 000, dielectric strength=100 V/mil) was obtained from Tusconix Inc. (7741 N. Business Park Dr., P.O. Box 37144, Tucson Arizona). In order to make the capacitor (4), the ceramic disk must be metallized on both sides. The disk was degreased, mounted in a aluminium mask exposing a diameter of 0.485″ and placed in a thin-film vacuum deposition chamber. Both sides of the masked disk were first flashed with Inconel (to provide a good base) and then vacuum coated with gold (min. 500 nm).

The inner conductor is made of three separate 304 stainless-steel elements (3), (6), (7). Elements (3) and (7) are 0.2443″ o.d. and are internally threaded at one end in order to mate with the G874 inner connectors (1). Elements (3) and (6) each contain an square groove (width w=0.110″ and diameter g=0.070″) and are hard gold electroplated (as above). The capacitor is pressed between elements (3) and (6), forming the electrical contacts. The compression force is derived from elements (6) and (7) which together act as a plunger: element (6) (of 0.212″ o.d.) slides inside element (7) which is hollow and contains a strong tungsten spring (not shown). A

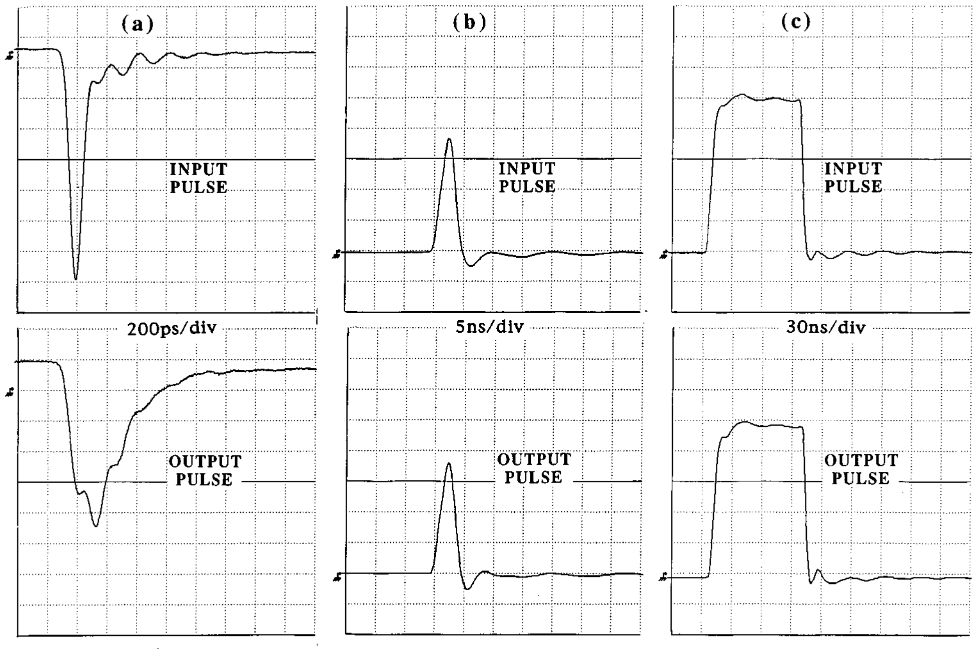

FIG. 3. Transmission of short-voltage pulses through the coupling capacitor assembly. The INPUT is measured before the capacitor, the OUTPUT after. (a) 100 ps FWHM. The OUTPUT pulse is distorted, attenuated, and broadened to about 500 ps FWHM. (b) 2.5 ns FWHM. The OUTPUT pulse is transmitted almost unchanged by the capacitor. (c) 30 ns FWHM. The OUTPUT pulse is transmitted almost unchanged by the capacitor, showing the particular advantage of high values of capacitance (6 nF) for transmitting analog waveforms.

kapton film (0.005″ thick, not shown) lies on the i.d. of the outer conductor (about 1.2 turns) to help center the capacitor and to prevent shorts. The 1 MΩ bias resistor (8) is spot welded to element (7) close to the end. This resistor is important because it blocks ringing between the anode and the high-voltage bias supply. A small vespel grommet (not shown) centers the resistor lead in the 0.125″ hole in the outer conductor (5). An improvement over this design would be to bring the high-voltage bias directly to the anode. This avoids the placement of the resistor inside the coupling capacitor and would improve the bandwidth. However, this requires modification of the MCP assembly.

IV. TESTING

After assembly, the coupling capacitor was tested for its capacitance and response to both fast (100 ps) and slower (2.5 ns, 30 ns) voltage pulses. A calibrated capacitance meter (Sencore, Model LC75) determined that the series capacitance of the assembled coupling capacitor was 6 nF. This relatively large value is important in order to avoid distortion (i.e., differentiation) of longer analog signals. The device was also tested for voltage breakdown by applying (in vacuum) 5 kV, first across the inner and outer conductors and, second, across the ceramic disk. No failures were observed. A typical operating voltage for an anode is less than 3 kV.

A 6 GHz bandwidth digital sampling oscilloscope (Tektronix 11801A, SD 30 head) was used to measure the response of the assembled coupling capacitor to a variety of voltage pulses. Two SMA-GR adaptors were used to install the device in the fast circuitry. The results of these experiments are shown in Figs. 3(a), 3(b), and 3(c). The ''OUTPUT'' pulse was measured with the coupling capacitor installed. The ''INPUT'' pulse was measured by replacing the device with a standard GR union. The bias resistor was externally grounded during these measurements.

We first consider Fig. 3(a), the response to a 100 ps FWHM input pulse. The timebase is 200 ps/div. This short pulse was obtained from a picosecond mode-locked Nd:YAG laser (Coherent, Antares) using a fast photodetector (Opto-Electronics, Model PD50). The small ringing seen in Fig. 3(a) top is due to slight impedance mismatches in the connectors. The response of the coupling capacitor is shown in Fig. 3(a) (bottom). It can be seen that the input pulse is distorted and broadened to about 500 ps FWHM after transmission. Therefore, we can suggest the bandwidth of the device is approximately 2 GHz. It is interesting to note that with the bias resistor removed, the 100 ps input pulse was essentially undistorted by the coupling capacitor.

In order to measure the response of the device to longer analog pulses, we replaced the picosecond laser/photodiode with a variable width pulse generator (Stanford Research DG535). In Fig. 3(b) we applied a 2.5 ns FWHM pulse. The timebase is 5 ns/div. The slight overshoot seen in Fig. 3(b) top is due to the pulse generator itself. The response of the coupling capacitor is seen in Fig. 3(b) (bottom). The voltage pulse is essentially both undistorted and unattenuated. In Fig. 3(c) we applied a 30 ns square pulse to the capacitor in order to simulate the response to longer analog waveforms. Here the timebase is 10 ns/div. This voltage pulse is also unaltered by the coupling capacitor. In another experiment (not shown), a small disk capacitor (500 pF) replaced the UHV coupling capacitor. This completely distorted the 30 ns pulse, transmitting only the rising and falling edges, and showing the importance of having a large value of capacitance for experiments with analog signals.

The coupling capacitor was attached to a MCP detector (Galileo FTD 2003) and installed into an UHV photoelectron spectrometer. The entire UHV machine was baked by internal 500 W quartz lamps for approximately 72 h. The temperature of the detector/capacitor itself was measured to be 190 °C during the bakeout procedure. The ultimate vacuum obtained in this turbo-pumped system was 2×10^{-10} Torr. The capacitor was tested again for high-voltage breakdown, without failure. The response of the electron detector/coupling capacitor to a photoelectron signal produced by our femtosecond lasers was clean, ring-free pulses which were bandwidth limited (by our present amplification and detection electronics) to 300 MHz. This coupling capacitor has been in continuous operation in our laboratory for two years and has never failed or arced over.

V. DISCUSSION

In photoelectron spectroscopy, it is often necessary to operate the detector with the anode biased at a high positive voltage, requiring a decoupling of the high voltage from the sensitive timing electronics which follow. We have demonstrated a simple design for a GHz bandwidth coaxial UHV decoupling capacitor which has the particular feature of large capacitance. This design also fits onto commercially available MCP detectors and provides a very convenient bias tee with blocking resistor to supply the high voltage to the anode. The materials involved are completely UHV compatible and bakeable to 200 °C.

The capacitance of the unit was measured to be 6 nF, a relatively high value. This is particularly useful for the undistorted transmission of analog waveforms. Smaller value of capacitance tend to differentiate longer waveforms. The impulse response of the coupling capacitor (to a 100 ps voltage pulse) indicated a bandwidth of about 2 GHz. The unit transmitted longer pulses (2.5 and 30 ns) with minimal distortion or attenuation.

We hope that this simple design will be useful to researchers considering fast timing techniques (such as time-correlated counting) in combination with photoelectron spectroscopy.

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