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CAPACITOR BRIDGE

Overview:

In this lab students will learn to measure the capacitance of an unknown capacitor by building a capacitor bridge circuit using a known capacitance.

Background:

Electronic devices are an indispensable part of daily life. Capacitors are used in electronic circuits as filters, resonant circuits, integrators, differentiators, waveform generators, coupling capacitors, bypass capacitors, energy storage devices etc. [1] A capacitor is made of two conductors separated by a dielectric in between. When a voltage (V in volts) is applied across a capacitor (Capacitance C in farads), each of the parallel plates can store a charge (Q in coulombs) equivalent to

$$Q = CV \quad (1)$$

The capacitance is measured using a capacitance meter. Commercially available capacitance meters are not often handy to measure small changes in capacitances of nanodevices and they are difficult to implement in nanodevice circuits due to their size limitations and presence of long cables. Hence it is necessary to figure out new methods to measure capacitances in a nanoelectronics circuit. Capacitor bridge circuits seem to be an option here. To find the value of the unknown capacitance, we can make a capacitor bridge circuit [2] as shown in figure 1.

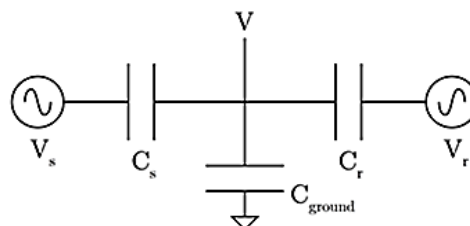


Figure 1: Capacitor Bridge Circuit [2]

Let C_s be the unknown capacitance which is connected to an AC voltage source V_s , C_r be the known capacitance connected to an AC voltage source V_r . V is the voltage across bridge point between the two capacitors and C_g is the parasitic capacitance (C_{par}).

At the bridge point,

$$C_s V_s + C_r V_r = C_T V \quad (2),$$

$$\text{where } C_T = C_s + C_r + C_g \quad (3)$$

Now we can balance the bridge by setting the phase and amplitude of V_r such that $V = 0$. Thus,

$$C_s = \frac{C_r}{V_s} V_r \quad (4)$$

Almost all circuit elements, including the junctions and cables has some stray capacitance and it affects the real capacitance value of the capacitor.

Research Connection:

Researchers are constantly in search of novel tunable, functional, flexible and cost-effective nanomaterials for varied applications (transistors, supercapacitors, solar cells, energy generation, transfer and storage devices etc.) and they show interesting properties at nanoscale.

Cobden Research Group/ Nanodevice Physics Lab use various 2D nanomaterials/electronic systems like graphene, hexagonal Boron Nitride (h-BN), WSe_2 , MoS_2 etc. to make nanoelectronics devices. For example, a simple capacitor can be made using flexible 2D materials like graphene and graphite as gate electrodes and h-BN as dielectric. They explore and study the fundamental physics like many-body and quantum effects, low temperature physics, electronic excitations etc. under the influence of electric and magnetic fields, even at cryogenic temperatures. These devices are microfabricated using thermo-mechanical exfoliation, electron beam lithography, etch and deposition techniques, wire bonding etc. to make contacts and connections [Figures 2 and 3].

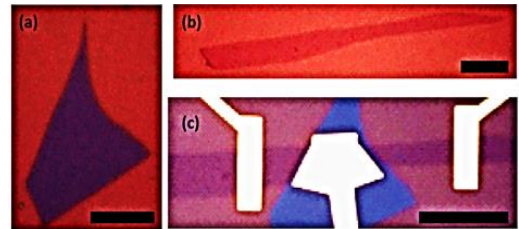


Figure 2: Scale bar: 10 microns. (a) hBN, (b) graphene, (c) contacts and gates fabricated by electron beam lithography [4]

A thorough understanding of the physics governing the materials at nanoscale is crucial for their application in industry. It would be possible to tune material properties like density of states, band gap, electronic excitations, transport, capacitance etc. by understanding the physics behind. Capacitor bridge allows researchers to find capacitance of these nanodevices with almost femtofarad resolution. This could also be used for studies at cryogenic temperature.

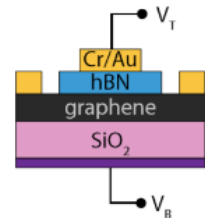


Figure 3: Dual Gated Nanodevice [4]

Materials:

- 2 Function generators [BK Precision, 4078 – 25MHz Dual Channel Arbitrary/Function Generator; Stanford Research Systems Model DS345 – 30MHz Synthesized Function Generator]. [Figure 4]
- Lock in amplifier [Stanford Research Systems, Model SR830 DSP]
- Bread board
- Two commercial capacitors of nanofarad or picofarad range. Select one as known capacitor and the other one as unknown capacitor.
- Capacitance Substitution Box [Model 237, Phipps & Bird, Inc., Serial # 0192380-134]
- Connection wires [3M jumper wire kit]
- COLEMAN cable 993317
- BNC cables
- Banana sockets
- Capacitance meter [CEN-TECH P37772. Plug in the capacitor terminals on C_x and select the proper range]
- Oscilloscope [Tektronix TDS 3032B]

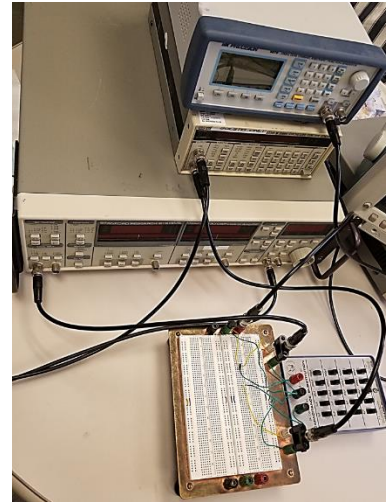


Figure 4: Capacitor Bridge Circuit

Estimation of unknown capacitance using capacitor bridge

Objective:

To measure the capacitance of an unknown capacitor by building a capacitor bridge circuit using a known capacitance.

Procedure:

1. Identify the capacitance value of known capacitor using the color code, manufacturer data sheet or using a capacitance meter and record it.
2. Take a breadboard and connect the known and unknown capacitor.
3. Connect the known capacitance (C_r) to the function generator (V_r) using wires, banana plugs and BNC cable. [Figure 4]
4. Similarly, connect the unknown capacitance (C_s) to the other function generator (V_s).
5. Connect a wire from the capacitor bridge point to the lock in amplifier (input A/I) using a BNC cable to measure the V .
6. Connect the Coleman cable from the channel 1 REF IN/OUT plug at the back side of BK Precision to the input TIMEBASE plug at the back side of the DS345 generator. [Figure 5]



Figure 5

7. Connect a BNC cable from the SYNC output on front side of the DS345 generator to REF IN of the lock in amplifier.
8. Now set both the function generators at the same frequency, say, 5000 Hz. The lock in amplifier reading Voltage V should also record the same frequency.
9. Keep the voltage offsets as zero in both the function generators.
10. Now set the amplitude and phase of V_r such that $V = 0$.
11. Record the amplitudes of V_r and V_s .
12. Now use the capacitance bridge equation (4) to find the unknown capacitance.
13. You may also measure the capacitance of the unknown capacitor using a capacitance meter, manufacturer data sheet or color code.
14. Find the percentage error between the measured and calculated values. Check whether the error falls within the tolerance indicated by the manufacturer and try to comment about the sources of uncertainty. Students could also use the oscilloscope to see the waveforms and the changes.
15. Write a lab report with all the details of your experiment.

Extensions:

Estimation of parasitic capacitance and the influence of cable length

Objective:

To get an estimate of the parasitic capacitance or stray capacitance present in an electronic circuit from the BNC cables and to study the influence of cable length on parasitic capacitance.

Theory: Balance the capacitor bridge circuit by setting the phase and amplitude of V_r such that $V = 0$. Record the amplitudes of V_r and V_s . Now change V_r by ΔV_r keeping the V_s constant, then equation (2) becomes $C_T(V + \Delta V) = C_S(V_s + \Delta V_s) + C_r(V_r + \Delta V_r)$ and we get $\Delta V = \frac{C_r}{C_T} \Delta V_r$

Thus, $C_{par} = \frac{C_r}{\Delta V} \Delta V_r - (C_s + C_r)$ (5)

Procedure:

1. Use the same circuit as above.
2. Record the value of C_r and C_s .
3. In the capacitor bridge circuit, set the phase and amplitude of V_r such that $V = 0$.
4. Record the amplitudes of V_r , V_s and V . If your voltage source reads the x and y components of voltage, calculate V using the equation $V = \sqrt{(V_x^2 + V_y^2)}$
5. Now change V_r , say $\Delta V_r = 3 \text{ mV}$ keeping V_s constant.
6. Record the amplitudes of V_r , V_s and V .
7. Calculate parasitic capacitance using equation (5).
8. Vary the BNC cable length used to connect the capacitor bridge point and lock in amplifier. Calculate the parasitic capacitance for at least 3 different cable lengths.

References:

1. The Art of Electronics, Paul Horowitz and Winfield Hill.
2. Imaging Transport Resonances in the Quantum Hall Effect, G. Steele, MIT Thesis (2006).
3. An integrated capacitance bridge for high-resolution, wide temperature range quantum capacitance measurements, Review of Scientific Instruments 82, 053904 (2011).
4. Electronic compressibility of layer-polarized bilayer graphene, Physical Review B., 85, 235458 (2012).

Sources:

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