EEE118: Electronic Devices and Circuits
Lecture V

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Last Lecture: Review

1. Finished the diode conduction state example question from lecture four.

2. Introduced the Light Emitting Diode (LED) and direct *vs.* indirect band-gap.

3. Performed a calculation to set the operating point of the LED.

4. Introduced the Zener Diode and considered the Zener effect and Impact Ionisation.

5. Very briefly considered a voltage regulating circuit using a Zener diode. (more later)

6. Introduced the Schottky Diode.

Outline

Pulse Circuits with Resistors & Capacitors

- These sort of circuits are found in measurement systems for timing and can be used to help retrieve information from noisy systems (phase sensitive detection) and in digital systems (clock distribution etc.) and in high frequency applications such as radar systems.

- In this course we're interested in understanding what goes on in the circuit and doing some calculations rather than derivations. Derivation is on the handout.

- All first order RC circuits have a transient or time domain response that involves $e^{\left(\frac{-t}{\tau}\right)}$ where τ is dependent on the circuit not on the properties of the pulse and t is time.

- τ (greek: *tau*) is the time constant which has units of seconds. $\frac{volts}{amps} \frac{coluombs}{volts} = \frac{coulombs}{\frac{coulombs}{seconds}} = seconds$

Pulse Circuit: "Low Pass" RC Example
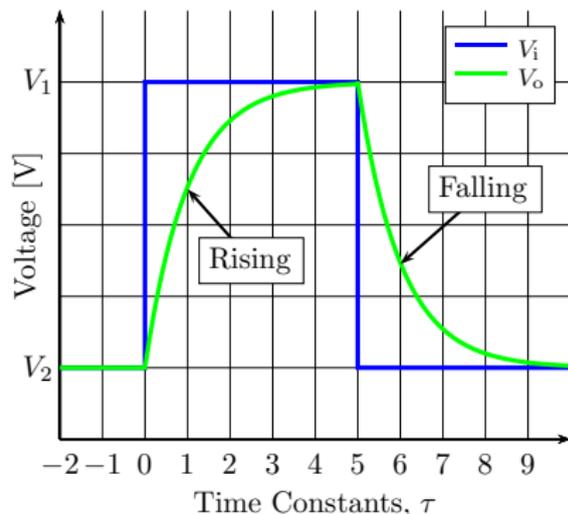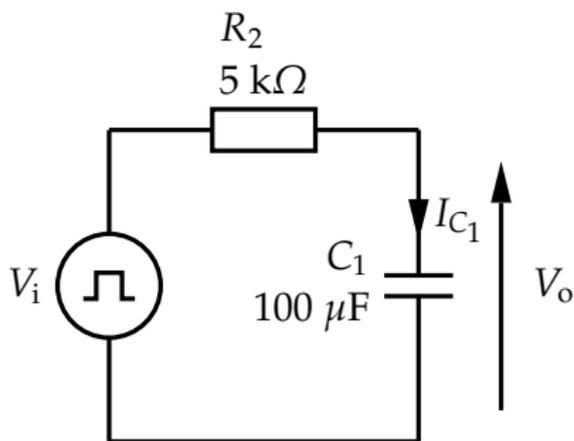
Rising: $V_o(t) = (V_1 - V_2)\left(1 - \exp\left(-\frac{t}{\tau}\right)\right) + V_2$, $t = 0$ at the start of the pulse

Falling: $V_o(t) = (V_2 - V_1)\left(\exp\left(-\frac{t}{\tau}\right)\right) + V_2$, $t = 0$ at the end of the pulse

$V_2 - V_1$ is the aiming voltage, the exponential gives the shape and V_2 is the offset

Pulse Circuits

- Often circuits which operate using pulses have several capacitances in them as well as resistors and diodes.
- In some cases the capacitance is used intentionally. In other cases the capacitance is "stray" or "parasitic" i.e. it is not desirable.
- In many cases there are several capacitances and the problem is taxing, however it can often be reduced to just a single dominant capacitance.
- An excellent example of a pulse circuit problem without a diode is the 10:1 oscilloscope probe circuit, but that will have to wait for EEE225 and the second year Amplifiers Laboratory.
- Problem Sheet 3 is devoted to these sorts of circuits[1].

The example here appears somewhere in the first year...

---

[1]For more, see Millman and Taub, "Pulse and Digital Circuits", 1956 or "Pulse, Digital and Switching Waveforms", 1965
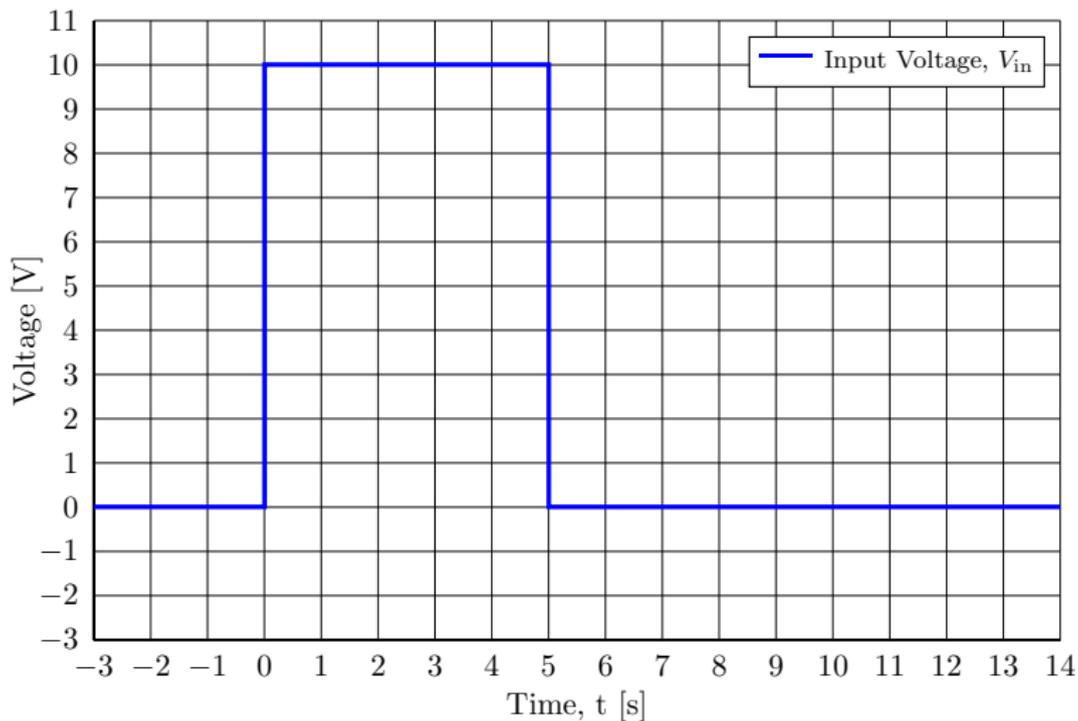
Pulse Circuit Example
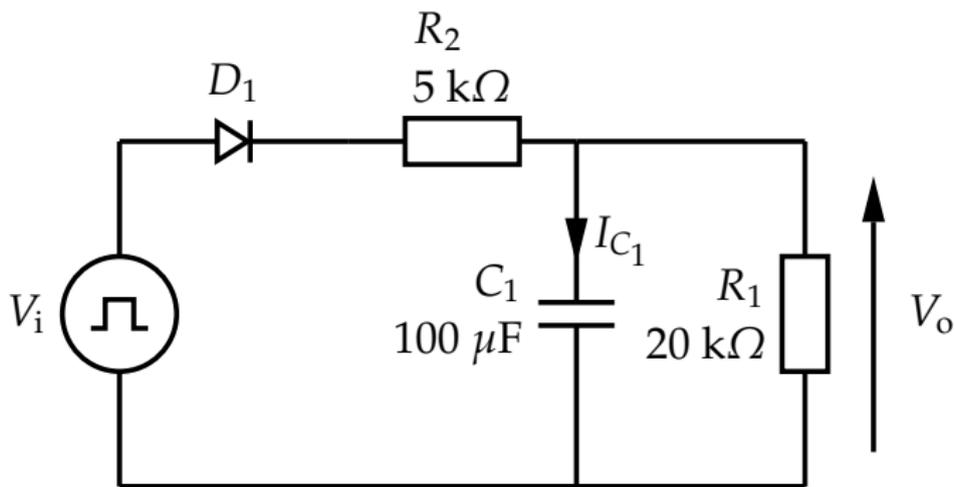
Assumptions:

- When D_1 is conducting it has 0 V across it (*not* 0.7 V)
- D_1 has no series resistance.
- C_1 is initially discharged so V_o is initially 0 V, unless the question says otherwise.

The input, V_i, is a single 0 to 10 V pulse of 5 seconds duration. A graph may or may not be provided so it's a good idea to learn how to interpret a description of the waveform.

Description of Operation

$t \geq 0$ & $t \leq 5$ seconds

$V_{in} = 10$ V, the diode is forward biassed. C_1 is charged by V_{in} through R_2 causing V_o to rise exponentially towards a maximum or aiming voltage. I_{C_1} is initially a maximum value at $t = 0$, it then falls exponentially towards zero. Some of the current in R_2 flows in R_1 complicating the problem!

$t > 5$ seconds

The pulse has ended, $V_{in} = 0$. The capacitor is now the source of energy in the circuit. The diode is reverse biased. It stops conducting when the current in it falls to zero at t = 5 s. The capacitor can not discharge through R_2 because the diode is high impedance. C_1 discharges through R_1 only. Because R_1 is larger than $R_2//R_1$ we should expect C_1 to take longer to discharge than to charge.
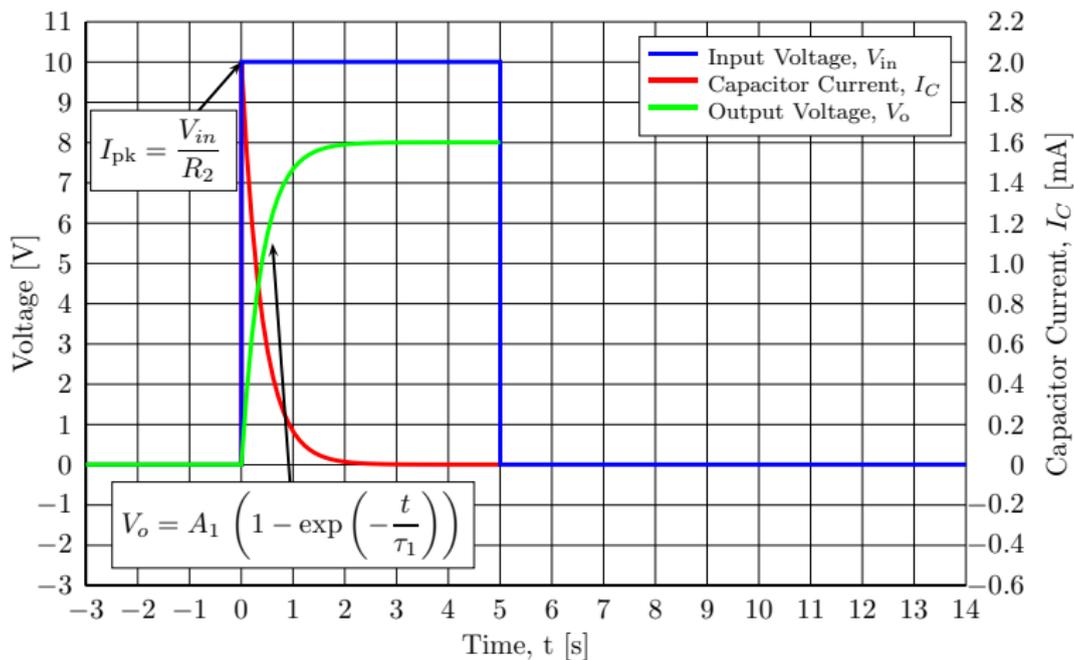
A_1 is 8 V in this case and I_{pk} is 2 mA. τ_1 the time constant is determined by the components involved $\tau_1 = (R_2//R_1) \, C_1$. The expressions for exponential rise to maximum and exponential decay are derived in the handout.

$t \geq 0$ & $t \leq 5$ seconds

- C_1 charges up from V_{in}, current flows from V_{in} through R_2 into C_1 and R_1
- V_o rises exponentially towards a maximum.
- I_C starts at a maximum and falls exponentially as the voltage across R_2 falls due to the voltage across C_1 getting larger.
- Since C_1 is initially (at $t = 0$) discharged, $V_o = 0$ V so the biggest value of I_{C_1} is at $t = 0$ and is given by Ohm's law $\dfrac{V_{in} - V_o}{R_2}$.
- The aiming voltage of V_o is the voltage that would exist across the capacitor if it had been charged up for a long time and the voltages and currents had reached a steady state. In this case the capacitor can not charge to a voltage greater than the potential division of V_{in} by R_2 and R_1.
$$A_1 = V_{in} \frac{R_1}{R_1 + R_2}$$
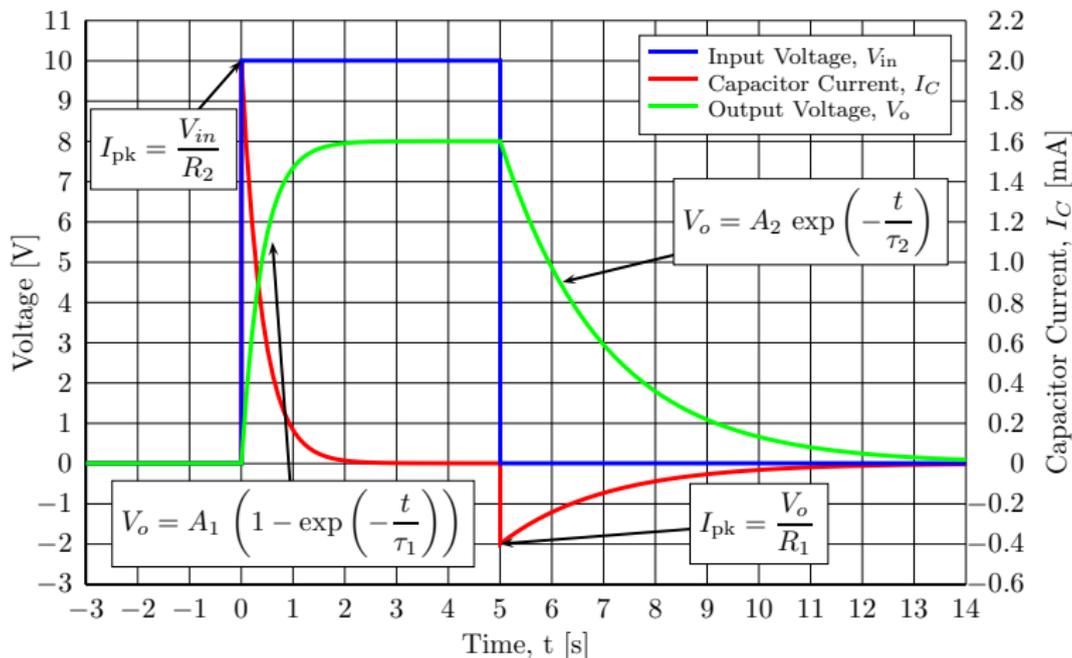
I_C changes direction, hence negative values. τ_2 is larger than τ_1. The negative peak current is given by Ohm's law using the voltage across C_1 at $t = 5$ s and R_1. $I_{pk} = -\frac{7.999}{20 \times 10^3} = -399.95 \ \mu$A.

$t > 5$ seconds

- At the end of the pulse $t = 5$ s, V_o has reached ≈ 8 V
  $V_o = 8 \left(1 - \exp\left(-\frac{5}{4\times 10^3 \cdot 100\times 10^{-6}}\right)\right) = 7.999$ V)

- I_{C_1} has fallen to nearly zero
  $I_{C_1} = 2 \times 10^{-3} \exp\left(-\frac{5}{4\times 10^3 \cdot 100\times 10^{-6}}\right) = 7.453$ nA

- V_i falls to zero, I_{R_2} falls to zero, and the diode switches off.

- The circuit becomes C_1 and R_1 in parallel, all else can be ignored.

- C_1 is the source of energy and this energy is lost as heat in R_1 as C_1 discharges to zero.

- The time constant for this discharge is $\tau_2 = R_1 C_1$.

Derivations for exponential expressions can be found in most undergraduate circuit's books e.g. Smith & Dorf, "Circuits Devices and Systems".

Puzzle

Why is $\tau_1 = (R_1 // R_2) \ C_1$?

Use Thévenin's theorem. We are not interested in the Thévenin voltage (it's A_1). What resistance does the capacitor "see" looking back into the circuit. This is the resistance in the time constant and the Thévenin resistance. Replace all sources by their internal resistances. The diode has no internal resistance (it's ideal).
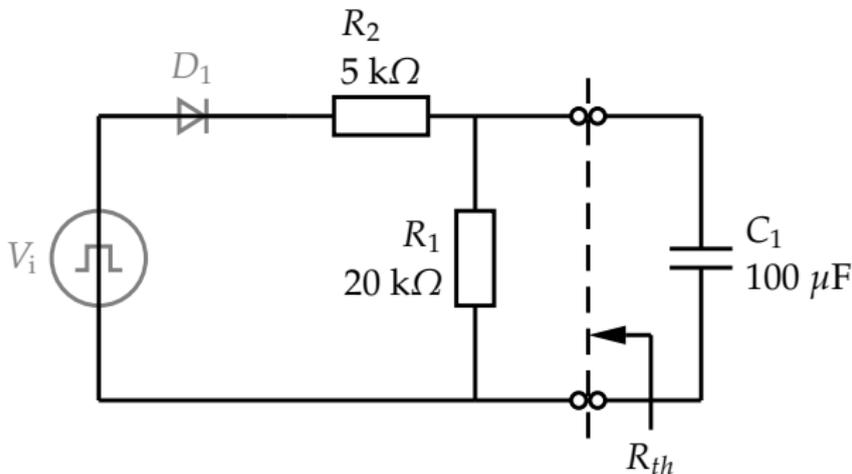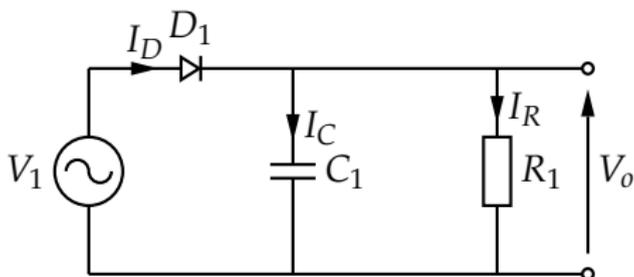
Five Diode Circuits

Five common circuits consisting of resistors capacitors and diodes will be examinable in this course, including:

1. Peak detector
   - e.g. AM radio demodulator
2. Voltage clamp
   - e.g. Preventing switching transistor saturation, distorting guitars etc.
3. Voltage multiplier
   - AC to DC conversion with doubling, many specialist PSU applications.
4. Diode rectifier circuit (three types of power supply)
   - Half-wave (one diode)
   - Full-wave (two diode)
   - Bridge (four diode)
5. Zener diode voltage regulator
   - Stabilise DC voltages having a small AC component or ripple
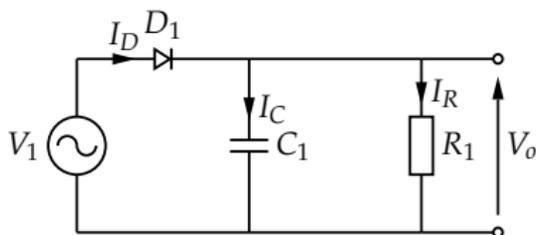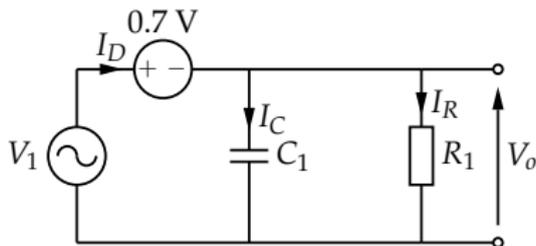
Peak Detector

One of the commonest applications of diodes is the conversion of an alternating current into a unidirectional current. This conversion process occurs in the signal detector parts of radio based systems and in power supplies designed to convert power from an alternating current distribution system - such as the UK's 50 Hz land based power distribution system or the 400 Hz distribution systems found in marine and airborne applications - into a good quality direct current source for electronic circuitry. Signal based applications of rectifiers will be discussed first.

Peak Detector

The key elements of source, V_1, diode, D_1, and capacitor, C_1, are connected in series and it is quite common to find a resistor, R_1, in parallel with the capacitor. The source may be a transformer secondary as is common in radio circuits or an amplifier output as is more typical of instrumentation systems. The circuit has two distinct states based on the conduction or non-conduction of the diode.

1. The diode is conducting (above), capacitor charges
2. The diode is not-conducting (shortly), capacitor discharges

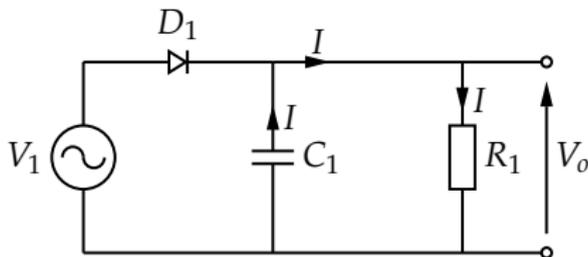## Peak Detector - Diode Conducting

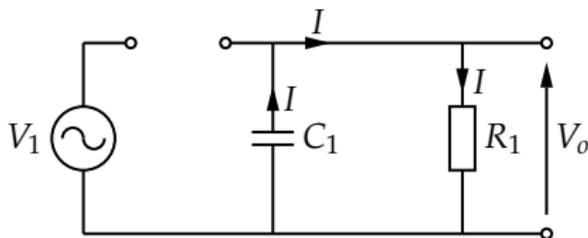Since the diode is conducting, replace with 0.7 V source.

The diode current charges C_1, and dissipates power in R_1. The charging current is limited by the diode series resistance. The voltage on C_1 can not increase above $V_1 - 0.7$.
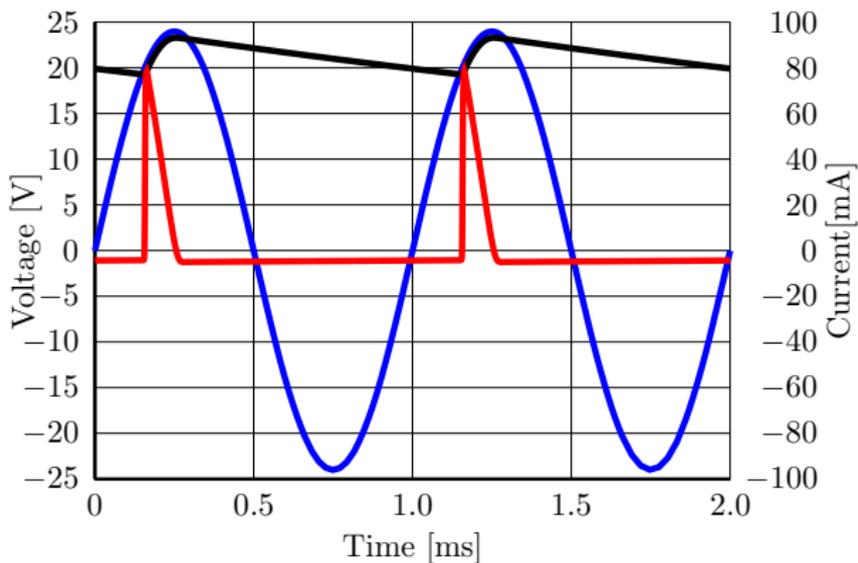
Peak Detector - Diode Not Conducting

Since the diode is not conducting, replace with open circuit

C_1 discharges through R_1. Voltage across C_1 falls as discharge proceeds. The shape of V_o is often a good approximation to a triangular waveform.

Peak Detector Graph

V_1: Blue, V_o: Black, I_{C_1}: Red

The integral of the capacitor current (area under the graph) sums to zero in one whole cycle.

Review

1. Introduced circuits driven by pulses.

2. Noted that, in EEE118 we are concerned with how to treat the circuit operation rather than how to solve differential equations (we will use the solutions without derivation).

3. Developed the idea of a time constant.

4. Looked at a low pass filter driven by a square pulse.

5. Worked through an "exam strength" pulse circuits question.

6. Introduced five diode circuits driven by sinusoids or waveforms derived from sinusoids. These form the basis of discussion from now until after the holidays.

7. Begun a description of operation for the peak detector circuit by thinking about the diode's conduction state as a function of time. A technique we will return to in the future.