e2v

Electrochemical Sensors Application Note 2
Design of Electronics for Electrochemical Gas Sensors

INTRODUCTION

This application note gives guidance on the design of electronic circuits for use with e2v electrochemical gas sensors. The information is provided for general advice and care should be taken to adapt the circuits to the particular requirements of the application. By following the recommendations of this application note the user should be able to achieve excellent performance with e2v electrochemical gas sensors.

Figure 1 shows the outline block diagram of a typical gas detection system using an electrochemical gas sensor.

The **electrochemical gas sensor** requires a **bias circuit** known as a **potentiostat** to maintain the correct bias potential between the sensing and reference electrodes as stated on the individual sensor datasheet. In many cases this will be 0 V but some devices require either a positive or negative bias potential.

The gas sensor produces an output current proportional to the gas concentration. A **current to voltage converter**, also known as a **transimpedance amplifier**, is required to convert the small currents from the electrochemical cell into a useful voltage for measurement.

The **analog to digital converter (ADC)** samples the output of the transimpedance amplifier and produces a digital reading of the voltage level. This is used by the **microprocessor** to calculate the actual gas concentration.

The microprocessor may drive a number of **outputs** depending on the applications. These could include an **LCD display**, a **4 – 20 mA interface**, a number of **alarms** or other outputs as needed.

At some point in the system there will need to be a **zero setting** and a **gain setting** adjustment. This could be implemented in hardware at the transimpedance amplifier, or in software within the microprocessor.

The inherent linearity of the electrochemical sensor means that for a simple application where only an analogue output is required, it is possible to dispense with the ADC and microprocessor. The voltage output of the transimpedance amplifier can be used to provide an analog reading of gas concentration directly. More critical applications may need to compensate for ambient temperature and/or pressure.
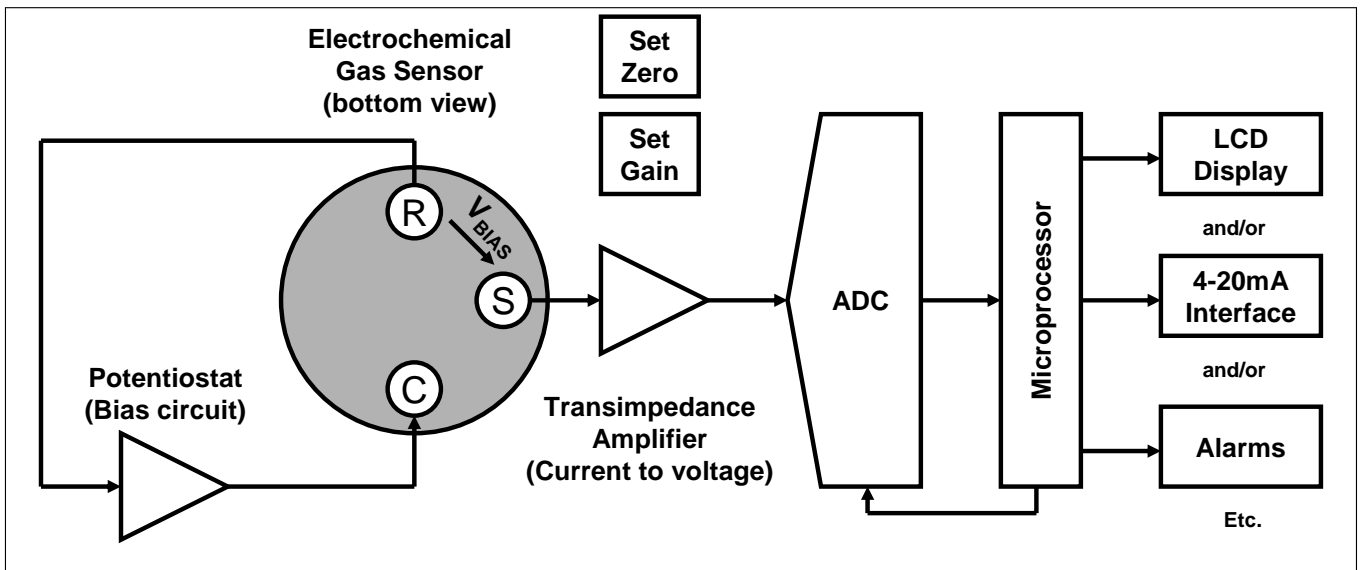

Figure 1 – Block Diagram of Typical Gas Detection System using an Electrochemical Gas Sensor

- **R:**   Reference Electrode
- **C:**   Counter Electrode
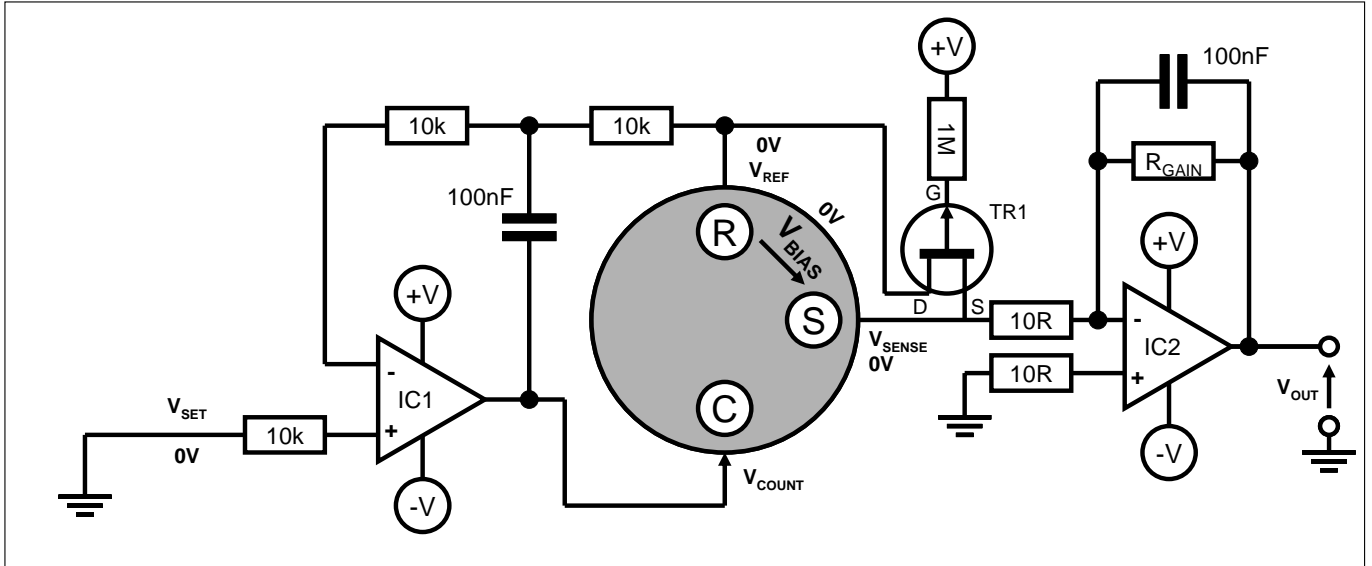- **S:**   Sensing Electrode (sometimes called the 'Working' electrode)

Figure 2 – Unbiased Sensor Circuit with Split Power Rails

UNBIASED SENSOR CIRCUIT (Figure 2)

Introduction to Biasing

The purpose of the sensor bias circuit (potentiostat) is to maintain the potential of the sensing electrode at a constant level with respect to the reference electrode. This is done by adjusting the voltage of a third 'counter' electrode.

The required bias level ($V_{SENSE} - V_{REF}$) varies according to sensor type and can be found on the relevant datasheet. It is summarised here for reference:

Sensor	Applied bias ($V_{SENSE} - V_{REF}$)	V_{OUT} Polarity
EC4-1-ClO2	0 V	Negative
EC4-50-ClO2	0 V	Negative
EC4-50-Cl2	0 V	Negative
EC4-500-CO	0 V	Positive
EC4-2000-CO	0 V	Positive
EC4-100-ETO	+300 mV	Positive
EC4-200-ETO	+300 mV	Positive
EC4-1000-ETO	+300 mV	Positive
EC4-1000-H2	0 V	Positive
EC4-100-H2S	0 V	Positive
EC4-1000-H2S	0 V	Positive
EC4-250-NO	+300 mV	Positive
EC4-2000-NO	+300 mV	Positive
EC4-20-NO2	0 V	Negative
EC4-20-PH3	0 V	Positive
EC4-1000-PH3	0 V	Positive
EC4-20-SO2	0 V	Positive
EC4-2000-SO2	0 V	Positive
EC410 (O2)	-600 mV	Negative

Table 1 – Bias Potential for e2v Sensors

Potentiostat Circuit

Figure 2 shows a typical potentiostat circuit using a positive and negative supply voltage. This configuration is simplest to explain but it can easily be adapted for single supply operation and this is described later.

Operational amplifier IC1 monitors the potential of the reference electrode, V_{REF} and applies an appropriate potential V_{COUNT} to the counter electrode to keep V_{REF} equal to V_{SET}. This potential will change as the gas concentration changes because it is supplying current into the counter electrode to balance the output current from the sensing electrode.

The majority of electrochemical sensors are 'unbiased' and so $V_{SET} = 0$ V. The potential of the sensing electrode is also held at 0V by the biasing effect of the output circuit so the result is zero bias between the V_{SENSE} and V_{REF}.

Maintaining Zero Bias during Power Down

TR1, a P-channel FET, maintains the zero bias between sensing and reference electrodes when the supply voltage is turned off. A low voltage on the gate causes the FET to conduct so that $V_{REF} = V_{SENSE}$. Holding this 0 V bias during power down enables the sensor to stabilise very quickly when the power is turned on again.

When the circuit power is reconnected, a high voltage on the gate of TR1 will cause the FET to stop conducting so that the op-amp can control the bias. TR1 should be chosen to have a positive gate-source cut-off voltage $V_{GS(OFF)}$ which is lower then the supply voltage. Transistors such as the J177 (leaded) or MMBFJ177 (surface mount) are often used. If a shorting FET is not used, the sensor may take a few hours to restabilise after turn-on.

Output Polarity

The output of electrochemical sensors is a current proportional to the gas concentration. For most gases electrons flow *out* of the sensing electrode (i.e. conventional current flows *into* the sensing electrode) which results in a positive output voltage from the circuit. However, for gases which undergo a reduction in the cell (ClO_2, CL_2, NO_2 and O_2), electrons flow *into* the sensing electrode (conventional current flows *out*) which results in a negative voltage from the circuit. See Table 1 for a summary.

Transimpedance Amplifier

The output current of the electrochemical sensor must be converted to a voltage using a transimpedance (current to voltage) amplifier. Figure 2 shows operational amplifier IC2 connected in this mode.

A 10R load resistor is recommended in series with the sense electrodes. This resistor forms an RC smoothing filter with the intrinsic sensor capacitance. It is possible to improve the response time by reducing the value of load resistor, but at the expense of higher output noise.

R_{GAIN} defines the gain of the amplifier in V/A. For example, if R_{GAIN} = 10k then:

Transimpedance gain $= 10^4$ V/A

From the sensor datasheet (e.g. EC4-250-NO):

Sensor sensitivity   = 400 nA/ppm
$= 4 \times 10^{-7}$ A/ppm

Then the system sensitivity is calculated as:

System sensitivity $= 4 \times 10^{-7} \times 10^4$ V/ppm
$= 4 \times 10^{-3}$ V/ppm
= 4 mV/ppm

It should be noted that the sensor datasheets give a range for the sensitivity. The gain resistor should be selected so that the output does not saturate at the maximum gas concentration in your application using a sensor with maximum sensitivity.

A capacitor may be fitted in parallel with the gain resistor to provide a high frequency cut-off to reduce any noise on the output.

The sensitivity will be found to reduce slightly over time (long-term output drift) and a figure is given on individual sensor datasheets. This change is typically less than 2% per month.

BIASED SENSOR CIRCUIT (Figure 3)

Figure 3 shows a potentiostat circuit for a biased sensor. This circuit is designed to provide a bias of +300 mV between the sense and reference electrodes by using a −300 mV V_{SET} supply.

Operational amplifier IC1 monitors the potential of the reference electrode, V_{REF} and applies an appropriate potential V_{COUNT} to the counter electrode to keep V_{REF} equal to V_{SET} (−300 mV).

The potential of the sensing electrode is held at 0 V by the biasing effect of the output circuit so the result is a +300 mV bias between V_{SENSE} and V_{REF}.

This +300 mV biasing arrangement is suitable for NO and ETO sensors. For oxygen sensors which require a −600 mV bias between V_{SENSE} and V_{REF} it is necessary to use V_{SET} = +600 mV. In this case the V_{SET} supply would be connected between +V and ground.

WARNING: Applying an incorrect bias voltage may damage the sensor.

Maintaining Positive/Negative Bias When Off

In some instruments the power to the bias circuit is deliberately maintained even when the instrument is turned off. This keeps the bias across the sensor so that it is stable and ready to use immediately the instrument is switched on. A backup supply such as a coin cell might be used for this purpose. The shorting transistor is not used in this situation.
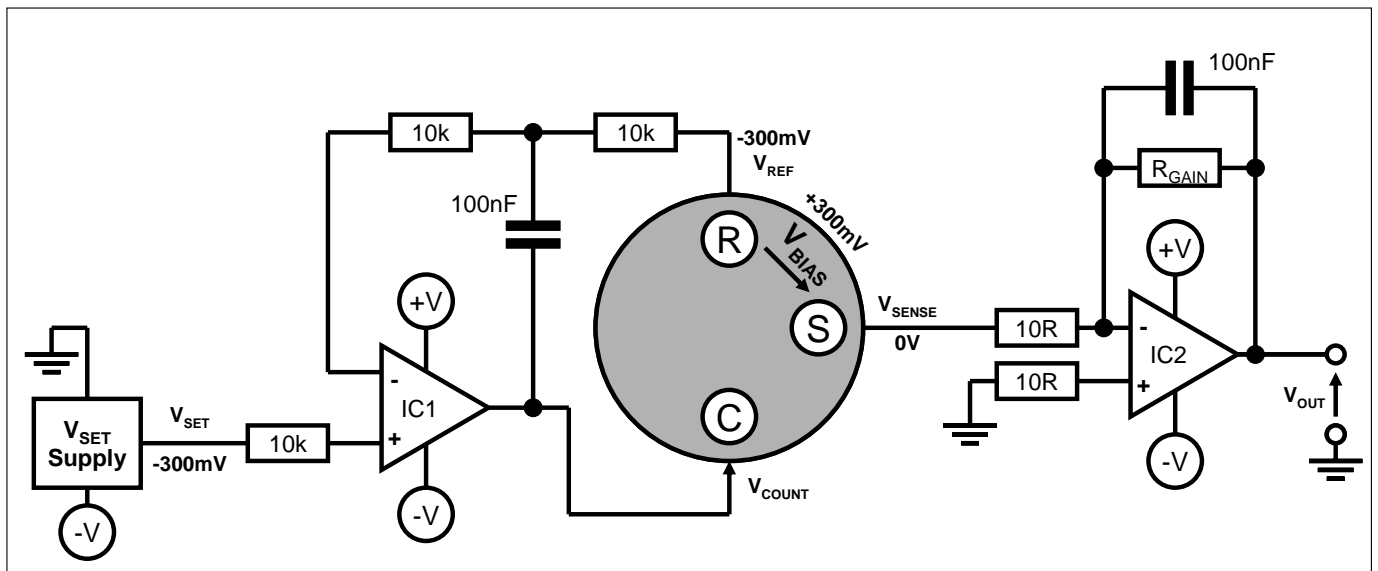

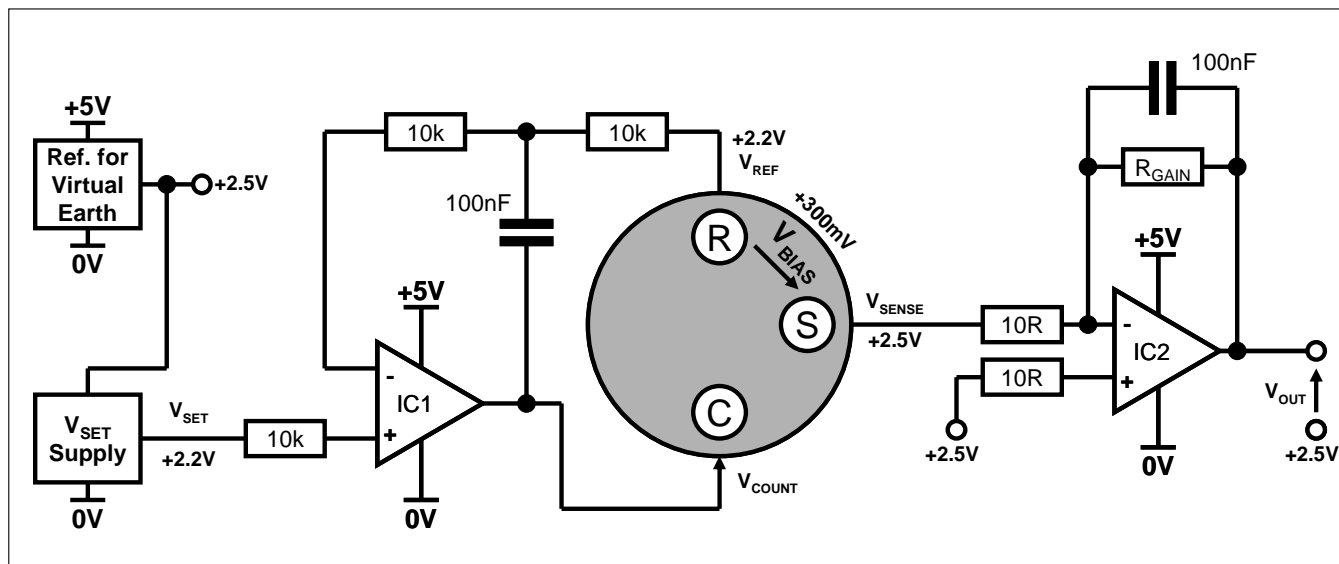**Figure 3 – Biased Sensor Circuit with Split Power Rails**

Figure 4 –Biased Sensor Circuit with Single Power Rail

BIASED SENSOR CIRCUIT WITH SINGLE SUPPLY (Figure 4)

Figure 4 shows another potentiostat circuit for a biased sensor but this time using a single 5 V supply. It is necessary to generate a virtual ground which is typically at half the supply voltage, in this case 2.5 V. A stable voltage reference should be used to generate the virtual ground.

The virtual ground is used to reference the output circuit so the sensing electrode will also be at 2.5 V. In order to achieve a +300 mV bias between V_{SENSE} and V_{REF}, it is necessary to have V_{SET} at 300 mV below the virtual earth. Therefore V_{SET} = 2.200 V.

The circuit can be adapted for even lower supply voltages but it may be necessary to change the virtual earth voltage to allow enough voltage swing. For example: an oxygen sensor requires a −600 mV bias so the reference electrode will be 600 mV above the virtual earth. The counter electrode may be another 1.1 V higher than the reference electrode which now totals 1.7 V above the virtual earth. If the supply voltage is 3 V it would be necessary to use a 1.25 V reference or lower for the virtual earth.

The above example also highlights the importance of using op-amps with a rail-to-rail output swing with low voltage power supplies. The next section gives advice on choosing a suitable operational amplifier.

OPERATIONAL AMPLIFIER SELECTION

Several parameters should be taken into account when choosing the operational amplifier for the bias circuit:

Input Bias Current

Ideally the potentiostat operational amplifier should not draw any current from the reference electrode. In practice the op-amp has an 'input bias current' and if this is too large it will affect the output current from the sensing (working) electrode, particularly at low gas concentrations. A general rule is to select an op-amp with an input bias current of less than 5 nA.

Input Offset Voltage

When the power is off the zero bias is clamped by the transistor TR1. However, when the power is turned on the zero bias is then maintained by the potentiostat circuit. A significant input offset voltage in the op-amp IC1 will cause a sudden small step in the actual bias on the sensor. Electrochemical sensors are sensitive to even small changes in bias voltage which can cause significant currents to flow because of the sensor's large capacitance. The sensor could take several hours to stabilise after a change in bias. Select an op-amp with an input offset voltage below 100 μV if possible, being particularly careful to check the offset the maximum operating temperature.

Input Offset Voltage Temperature Drift

The input offset voltage of the operational amplifier will change with temperature which results in a slight change in bias voltage. Therefore it is advisable to choose an op-amp with low input offset voltage temperature drift.

Output Voltage Swing

Careful consideration should be given to the required output swing for the operational amplifier particularly in low voltage systems.

The output of the potentiostat op-amp supplies the voltage to the counter electrode. This will change according to gas type and concentration. It is recommended that the op-amp be able to drive at least 1.1 V either side of V_{SET}. In low voltage circuits this will typically require an op-amp with rail-to-rail outputs.

Output Current Drive

The output of the potentiostat op-amp supplies a current into or out off the counter electrode which matches the current out of or into the sensing output electrode. Refer to the sensor datasheets to determine the maximum possible current in your application and the direction of current flow. Ensure that the selected op-amp is capable of sourcing or sinking the required current.

CALIBRATION

Set Zero

It will be necessary to set the zero point when zero gas (clean air) is applied to the sensor. This can be done in hardware by offsetting the voltage at the non-inverting input of IC2. However, if the output goes to a Digital-to-Analog Converter (DAC) and a microprocessor then it will be easiest to store a zero point in software as part of a calibration routine.

For an oxygen sensor it is not always necessary to set a zero because the normal operating point is near the maximum span. However, for increased accuracy the zero offset can be obtained using one of the following methods:

- Apply pure nitrogen and measure the output.
- Assume an offset of 30 μA at zero concentration (10% of reading at 21%).

Set Sensitivity

The sensitivity of the circuit (mV/ppm) can be changed by adjusting R_{GAIN}. This is done when a known concentration of gas is applied to the sensor. In an instrument with a microprocessor, the sensitivity can be adjusted in software as part of the calibration routine.

Temperature and Pressure Compensation

For increased accuracy, instruments may also compensate for the effects of ambient temperature and pressure.

BIAS CIRCUITS

Where a bias voltage is required it is important that the bias voltage is very stable. Small transient changes in bias voltage can affect the sensor output for many hours.

The bias voltage should be generated using a stable reference device such as a series or shunt voltage reference. The reference should be generated relative to the ground (split supply circuits) or virtual ground (single supply circuits).

Figures 5 and 6 shows examples of generating −300 mV (for a +300 mV biased sensor) and +600 mV (for a −600 mV biased sensor) using a 1.225 V shunt voltage, reference such as the LM4041 or LM4051. These are examples and the circuit operation should be checked carefully for the particular supply voltage and the selected reference device.

Finally, Figure 7 shows how an operational amplifier can be used to generate a virtual ground from a single supply.

CIRCUIT LAYOUT

It is recommended to keep all PCB track lengths very short, especially in the potentiostat and transimpedance amplifier circuits. Operational amplifiers should be well decoupled close to the IC. Further noise reduction can be obtained by over-sampling the output signal and averaging the data.
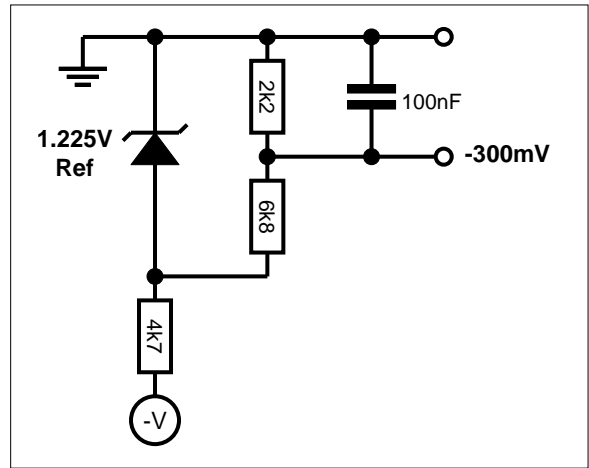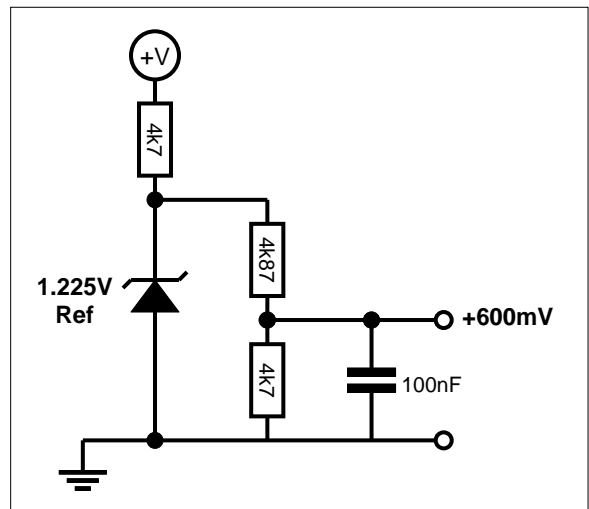

Figure 5 – Example Bias Circuit for -300mV
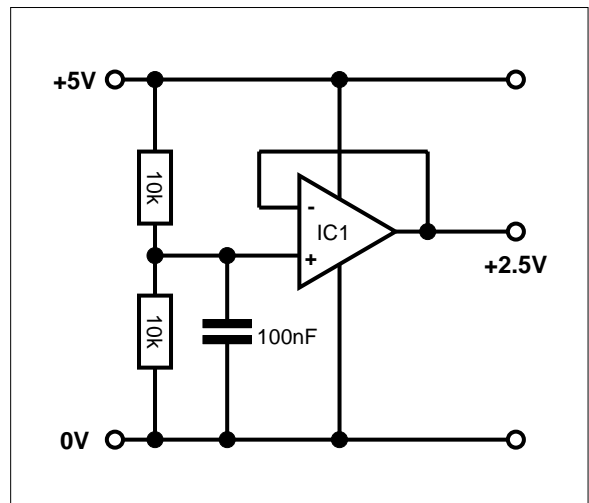

Figure 6 – Example Bias Circuit for +600mV

Figure 7 – Example Circuit to Generate Virtual Ground