Smart Sensors for IoT - Exam Winter Semester 2022

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Before starting, please write your name and Sciper number on the envelope and on each sheet.

You can use a paper copy of the lecture notes, of the exercises with solutions and your own notes. The use of electronic devices, such as mobile phones or tablets, is allowed if they are set in flight-mode. You can use any calculator.

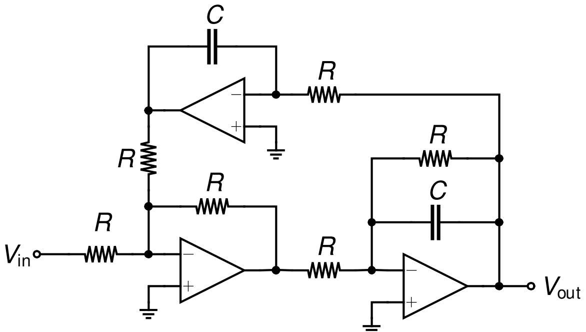
The maximum number of points obtainable in this exam is 30 and **you have 3 full hours**.

Multiple Choice Questions [10]

Select **one or more** answers for each of the questions below by circling the corresponding index letter with a pen.

- Each good answer = +1pt
- Wrong selected answer = -1pt
- No selected answer = 0pt

1. The figure below presents the schematic of a Tow-Thomas biquad filter.



C=1 nF and R=15.9 kΩ

What kind of filter is it:

(a) A bandpass filter with $f_0 = 10\,kHz$, $K = -1$ and $Q = 1$.
(b) A low-pass filter with $f_c = 10\,kHz$, $K = -1$ and $Q = 1$.
(c) A bandpass filter with $f_0 = 10\,kHz$, $K = +1$ and $Q = 1$.
(d) A high-pass filter with $f_c = 10\,kHz$, $K = +1$ and $Q = 1$.
(e) A low-pass filter with $f_0 = 1\,kHz$, $K = +1$ and $Q = 0.5$.

2. Consider the noise in devices and circuits and **mark all the correct statements**.

   (a) The equivalent noise bandwidth of a low-pass filtered white noise is larger than the filter cut-off frequency.

   (b) The noise of a resistor depends on the current flowing through it.

   (c) The power spectral density of shot noise is inversely proportional to frequency.

   (d) The noise power at the output of a 1st-order low-pass RC filter depends on R.

   (e) The power spectral density of thermal noise is proportional to temperature.

3. In a chopper stabilized amplifier, what is the impact of increasing the chopper frequency on the residual input-referred offset and input-referred noise?

   (a) It has no impact neither on the input-referred offset nor on the input-referred noise.

   (b) The residual input-referred offset decreases and the input-referred noise increases.

   (c) The residual input-referred offset increases and the input-referred noise decreases.

   (d) Both of them increase.

   (e) Both of them decrease.

4. FET-based biosensors can detect by electrical, mechanical and optical principles the concentration of various biomarkers in human biofluids. Select from their properties below the ones that are correct.

   (a) A FET-based biosensor is used to build amperometric sensor that can be combined with a reference electrode to measure the concentration of glucose in real-time.

   (b) The concentration of pH in human blood (serum) can be measured by monitoring the threshold voltage shift with a liquid gate FET based-sensor, without any specific functionalization of the gate oxide.

   (c) The long diffusion time of low-concentration analytes to very miniaturized nanosensors can be circumvented by using large sensors arrays of sensors, which may offer near real-time response times.

   (d) Capillary-force microfluidics to extract sweat as biofluid needs a low power pump that can be operated with the battery of a wearable.

   (e) The Nernst limit of ISFET sensitivity of $\frac{60mV}{pH}$ is a fundamental limit independent of the temperature of operation of the sensor.

5. Micro/Nano-Electro-Mechanical (M/NEM) resonator structures are designed as suspended mass with their resonance frequency varying in practice from kHz to GHz and being able to detect mass accretion.

   (a) A suspended MEM mass, operated as switch, can be used as inertial sensor, to measure the applied acceleration of the system for a car airbag actuation.

   (b) The quality factor, Q, of such MEM resonators depends on size (cross section) of the suspension arms of the suspended resonating mass.

   (c) If the air gap between the suspended mass and the fixed electrode is reduced by a factor of 5x and the applied DC voltage across the gap during operation is simultaneously increased by a factor 2x, overall the motional resistance Rm of the resonator can be reduced by more than 20'000x.

   (d) If one makes the same resonator beam design in silicon or carbon system, it would be expected that the resonance frequency is higher for resonators made of carbon.

   (e) Gas sensors based on suspended silicon beams covered by a specific absorbent polymer or oxide layer can benefit from the measurement principle of frequency shift of a resonating cantilever.

6. Energy harvesting is an emerging technology that can contribute to the autonomy of IoT sensory nodes and involves materials and devices able to capture energy from the sensor environment.

   (a) With present technology state-of-the-art, among the sensing, computing and communication functions of a wearable system, the wireless communication of data usually dominates energy consumption and limits the system autonomy.

   (b) The existing conventional solar cells are capable to generate in indoor light conditions (500 to 1000Lux) a power of the order of 5 Watt with an area of about $10cm^2$.

(c) There are two main reasons for which, with current energy harvesting technologies, we need to use hybrid solutions, combining energy harvesters and rechargeable batteries are: (1) to support the high energy required during data communication peaks, and, (2) to extend the battery lifetime.

(d) Energy harvesting from motion is a versatile energy harvesting technique for wearables that can produce, for instance, tens to hundreds of milliWats DC power. The main role of the additional circuitry needed to interface the piezoelectric energy harvesters and the IoT sensor is to manage the stored energy.

(e) Energy harvesting using TEGs from gradient temperature can be achieved with significantly higher efficiency if the temperature difference is higher than 3K but it can still work for a temperature

Problem 1: Linearized Wheatstone bridge [10pt]

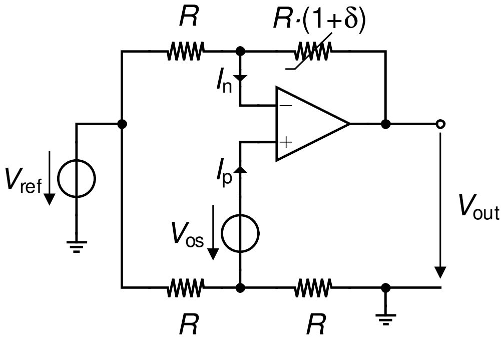


Figure 1: Linearized Wheatstone bridge.

The circuit in Fig. 1 is another linearized Wheatstone bridge, where the resistance $R \cdot (1+\delta)$ depends on temperature according to $\delta = \alpha \cdot (T - T_{ref})$. T [°C] is the operating temperature, $T_{ref} = 25$ [°C] is the reference temperature and $\alpha = 0.02\,°\mathrm{C}^{-1}$ is the temperature coefficient.

1.1 DC analysis

- Derive the output voltage as a function of the sensor resistance change δ by considering the OPAMP as ideal (that means zero input currents $I_p = I_n = 0$, no offset voltage $V_{os} = 0$ and infinite gain and bandwidth).
- What is the impact of the OPAMP input-referred offset voltage V_{os} on the output voltage?
- What is the impact of the OPAMP input leakage currents I_p and I_n on the output voltage?

1.2 Noise analysis

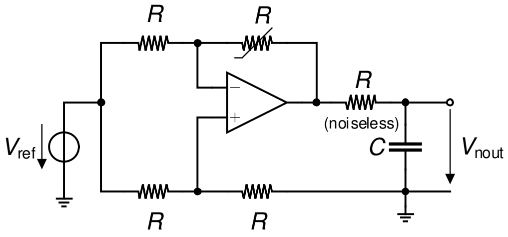


Figure 2: Linearized Wheatstone bridge with passive low-pass output filter.

We are interested in calculating the output thermal noise power spectral density (PSD) and output rms thermal noise voltage of the circuit shown in Fig. 2. The passive RC low-pass filter has been added to limit the thermal noise bandwidth. We will assume that the resistance of this low-power filter is noiseless. We also assume that the OPAMP has a high input resistance and hence its noise currents can be neglected. We only will account for the thermal noise of the bridge resistances and of the OPAMP.

Assume:

- $\delta = 0$,
- the four resistors in the bridge R show thermal noise,
- the resistance R of the low-pass filter can be assumed to be noiseless,

– the OPAMP has no $1/f$ noise and only an input-referred thermal noise PSD given by $S_{noa} = 4kTR_{noa}$.

Calculate for each noise source:

- The transfer function from the noise source to the output,
- the power spectral density of the output noise voltage due to the corresponding noise source and
- the output noise voltage variance.
- Finally, calculate the total output thermal noise PSD and output thermal noise voltage variance.

1.3 Sizing the systems

Assuming an ideal OPAMP (noiseless, infinite gain) and $T = 125\,\mathrm{K}$ calculate V_{ref}, R, and C to achieve:

- an output temperature-to-voltage gain G_T of $-0.1\,\mathrm{V}/°\mathrm{C}$;
- a cut-off frequency of $f_c = 100\,\mathrm{kHz}$ and
- an output thermal noise rms voltage of $V_{nout} = 10.2\,\mu V_{rms}$ at $T = 300\,K$, knowing that $k_B = 1.3807 \times 10^{-23}$ J/K and $\alpha = 0.02\,°\mathrm{C}^{-1}$.

Problem 2: Cortisol sensory patch [10pt]

Cortisol is a hormone released in response to stress. It is important to track its concentration in patients at risk of chronic disorders with serious negative impact on human health. Here, we show a wearable sensory patch that includes a **cortisol sensor** based on a platinum/graphene aptamer extended gate field effect transistor (EG-FET). Since the response to cortisol is highly dependant on the working temperature, a **temperature sensor** is integrated close to the cortisol sensor. The system is biased through a small battery, automatically recharged by a **thermoelectric generator** module.

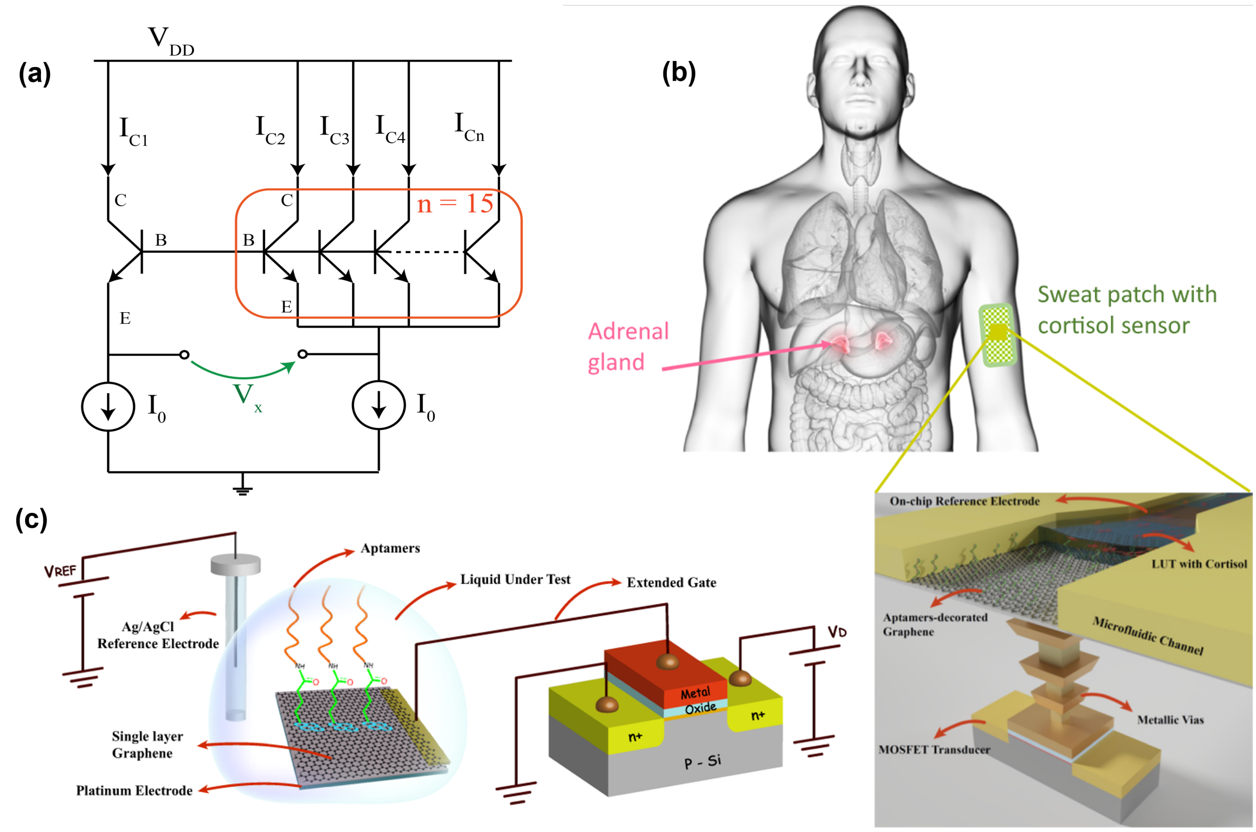


Figure 3: a) Temperature sensor schematic. b) Concept of the wearable device. c) Graphene-based extended-Gate device for cortisol sensing.

2.1 T sensor

The sensory patch system exploits a T sensor based on BJTs, exploiting the base-emitter junction as a diode and the collector current behaviour:

$$I_C(T) \approx I_S(T) \cdot (exp(\frac{V_{BE}}{V_T}))$$

where I_C is the collector current, V_{BE} the base-emitter voltage, and V_T is the thermal voltage $(\frac{k_B T}{q})$. The proposed sensor in Fig. 3 (a) is made by 16 **identical** BJTs with common base. 15 of them are biased with a constant current source I_0, and 1 of them is independently biased with an identical current source. The output measured quantity is $V_x = \Delta V_{BE}$.

Knowing that: $k_B = 1.38 \cdot 10^{-23} \frac{J}{K}$ and $q = 1.6 \cdot 10^{-19} C$:

- Calculate V_x when the body surface temperature is T = 309.5K.

- Calculate the temperature sensitivity $S_T = \frac{\Delta V_x}{\Delta T} \, [\frac{mV}{K}]$.
- **BONUS:** Propose an adequate circuit that would provide a constant current source I_0.

2.2 TEG

A voltage bias of 100 mV needs to be constantly delivered to the sensing device through a rechargeable battery connected to a termoelectric generator module kept in contact with the skin. The measured load resistance for the TEG is $R_{load} = 157\,\Omega$, the electrical resistivity of the n and p-type modules are respectively $\rho_n = 1.24\,m\Omega cm$, $\rho_p = 1.68\,m\Omega cm$, the surface body temperature and the external temperature are $T_{body} = 309.5\,K$, $T_{ext} = 291.15\,K$ and the Seebeck coefficient of the material couple is $\alpha = 168\,\mu V/K$. We know that the area of both n and p type elements is $A_n = A_p = 1.4\,mm^2$, the lengths are $L_n = 1.5\,mm$, $L_p = 1.15\,mm$ and the thermal conductivity of both materials is $k_n = k_p = 1.2 \cdot 10^{-2}\,W/cmK$.

- compute the figure of merit for the n-type material considering $\alpha_n = \alpha/2$ and the minimum number of n/p pairs needed to deliver a constant $V_{TEG\;output} = 100\,mV$.

2.3 Cortisol Sensing

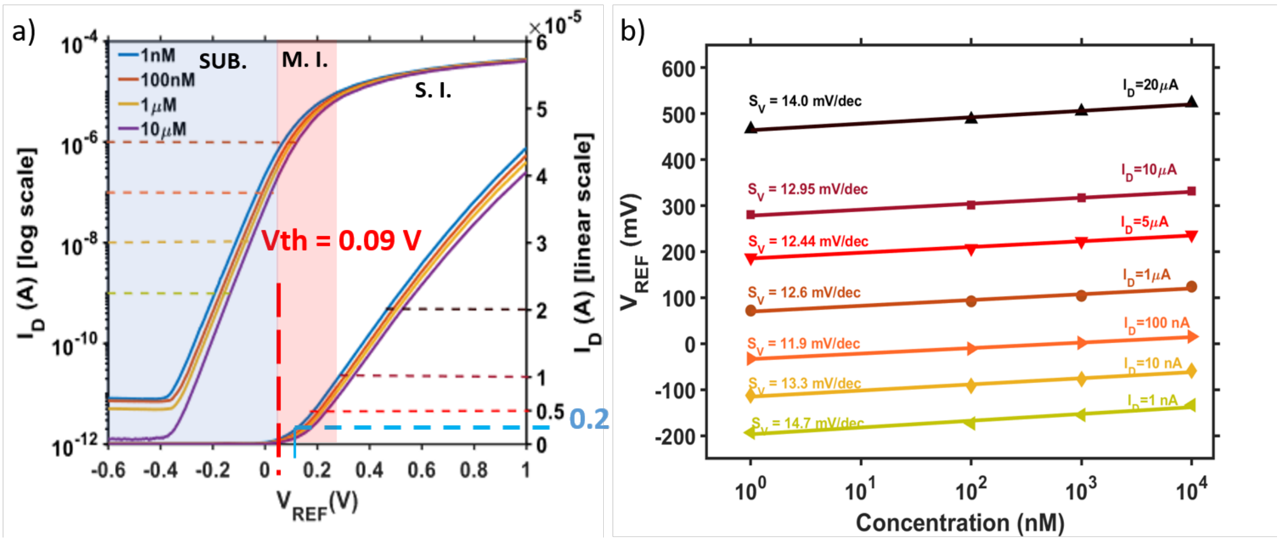


Figure 4: a) I_D-V_{REF} curves at constant Drain to Source voltage $V_{DS} = 100\,mV$ for different cortisol concentrations b) measured voltage sensitivity at constant current versus molar concentration of cortisol.

Considering the $I_D - V_{REF}$ curves and the voltage sensitivity calibration curves of the sensor in Fig. 4, answer the following question:

- You are asked to measure a sample containing a buffer solution with an unknown cortisol concentration. The EG-FET sensor should operate in the **moderate inversion region** (M.I. as shown in Fig. 4a) with a constraint on the output current, which should be lower than $1.5\,\mu A$. Based on the plots you are given, estimate the reference voltage sensitivity $S_v = \delta V_{REF}/\delta Conc$ versus the cortisol concentration in this regime of operation.

Considering the current sensitivity curves of the sensor in Fig. 5, answer the following question:

- Consider $V_{DS} = 100\,mV$ constant and the device biased in the moderate inversion region. What is the best voltage one should apply to the integrated reference electrode to sense the output current variation, given the measurement results in Fig. 5? Estimate the output current that one should obtain when measuring a test sample with a concentration of 100 nM with the device biased in this configuration ($I_{DS}(1\,nM) \approx 0.2 \cdot 10^{-5}\,A$).

Please, consider that all the questions can be answered without the use of the current MOSFET equations.

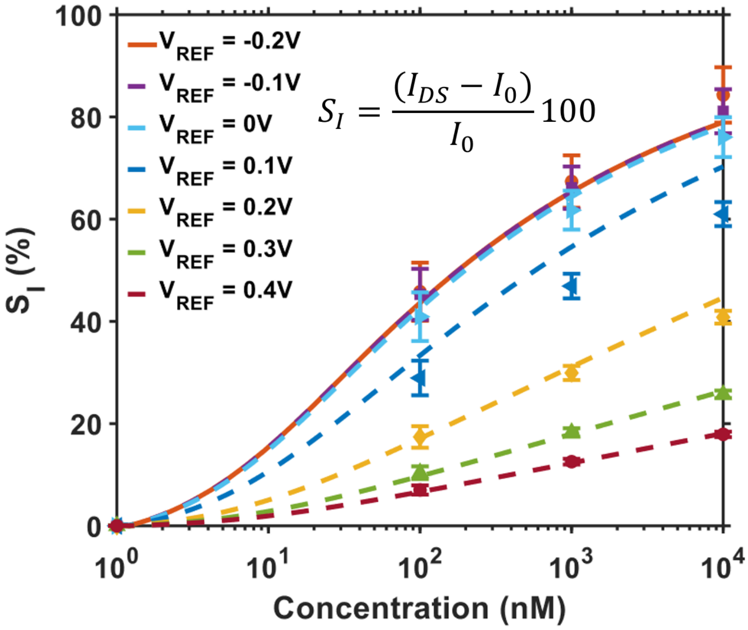


Figure 5: Measured current sensitivity showing the percentage of current variation for different cortisol concentrations at different constant reference voltages. The current level of reference is indicated as I_0 and equals the value of I_{DS} measured for 1 nM of cortisol concentration.