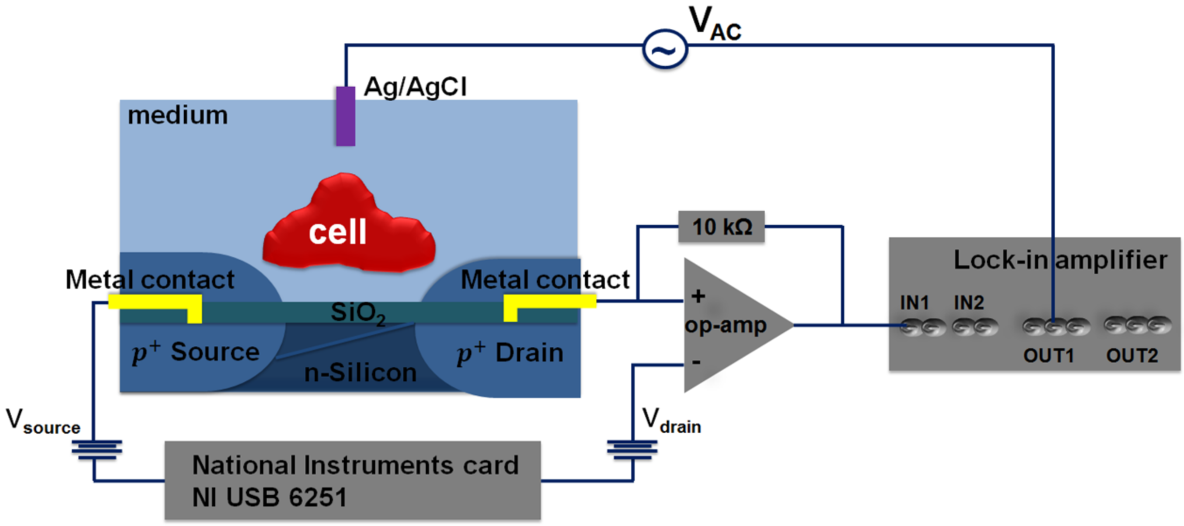
Electronic Supplementary Material (ESI) for Lab on a Chip.

Supporting information

A) Experimental setup

Figure 1S. Schematic diagram of the experimental setup with a fast lock-in amplifier.



B) Derivation of the analytical solution

The transfer function is defined by the ratio of the input and the output voltage of the amplifier.

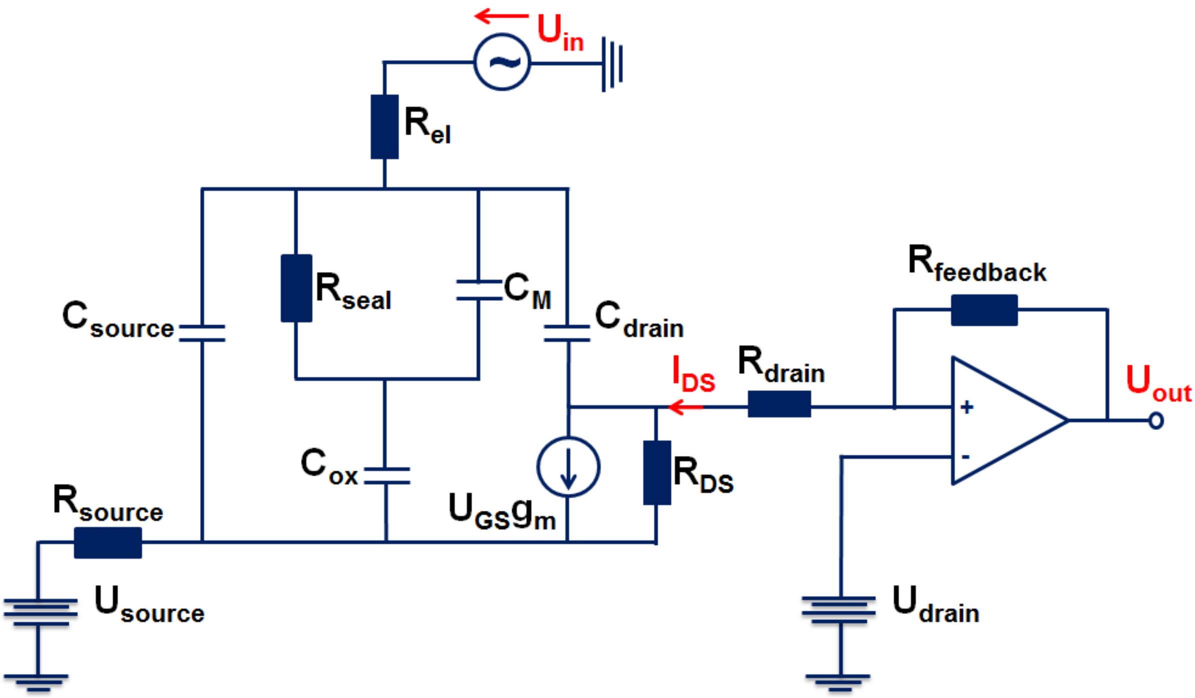
$$H(jw) = \frac{U_{out}(jw)}{U_{in}(jw)} \qquad (1)$$

The output voltage is then given by equation (2)

$$U_{out}(jw) = -R_{feedback} I_{DS}(jw) \qquad (2),$$

where $R_{feedback}$ is the feedback resistance in the transimpedance amplifier stage. In the following we will derive an expression for $I_{DS}(j\omega)$, which will then provide an analytical solution for the measured TTF-spectra $U_{out}(j\omega)$ for the simplified EEC presented in Figure 2S.

Figure 2S. A simplified equivalent electronic circuit, which describes a FET device in contact with an adherent cell on top of the transistor gate. The adhered cell can be modeled in a first approach by two elements namely the membrane capacitance C_M and the seal resistance R_{seal}.



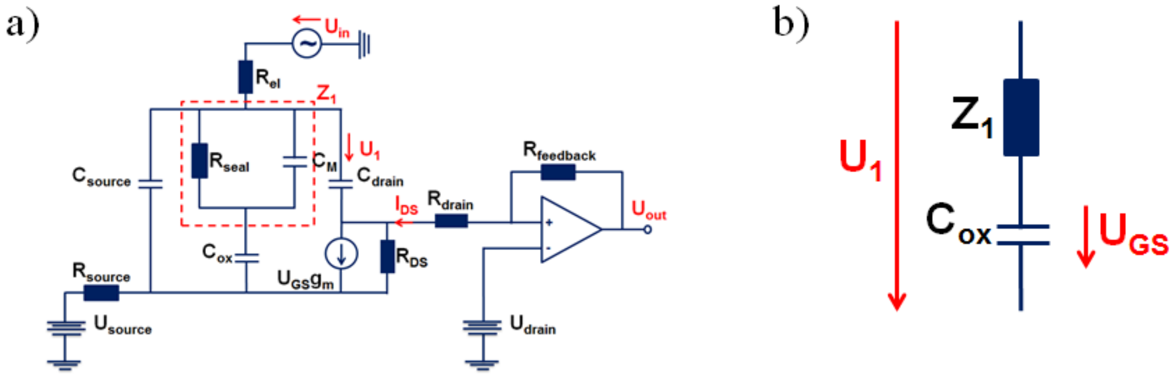
Based on Kirchhoff's first law the drain-source current I_{DS} is equal to:

$$I_{DS}(jw) = g_m U_{GS}(jw) - jwC_{drain}U_1(jw) \qquad (3),$$

where $U_1(j\omega)$ is the voltage across the drain contact line capacitance C_{drain} (Figure 3Sa). The gate-source voltage $U_{GS}(j\omega)$ can be found using a divider consisting of the impedance Z_1 and the gate oxide capacitance C_{ox} (Figure 3Sb). The impedance of the adherent cell Z_1, which is modeled by C_M and R_{seal} connected in parallel (Figure 3Sa), can be found using the rules for combining impedances in parallel:

$$Z_1 = \frac{R_{seal}}{1 + jwR_{seal}C_M} \qquad (4)$$

Figure 3S. (a) The parallel configuration of the membrane capacitance C_M and the junction resitance R_{seal} can be combined to the total impedance Z_1. (b) A voltage divider consisting of the impedance Z_1 and the gate oxide capacitance C_{ox}



Considering a voltage divider of two impedances in series (Figure 3Sb) (equation (5)), we can find an expression for the gate-source voltage $U_{GS}(j\omega)$ (equation (6)).

$$\frac{U_1(jw)}{Z_1 + 1/jwC_{ox}} = \frac{U_{GS}(jw)}{1/jwC_{ox}} \tag{5}$$

$$U_{GS}(jw) = U_1(jw)\frac{1 + jwR_{seal}C_M}{1 + jwR_{seal}(C_M + C_{ox})} \tag{6}$$

This expression can be included into equation (3):

$$I_{DS}(jw) = U_1(jw)\left(g_m\frac{1 + jwR_{seal}C_M}{1 + jwR_{seal}(C_M + C_{ox})} - jwC_{drain}\right) \tag{7}$$

$$I_{DS}(jw) = g_mU_1(jw)\left(\frac{1 + jw\left(R_{seal}C_M - \frac{C_{drain}}{g_m}\right) + w^2R_{seal}\frac{C_{drain}}{g_m}(C_M + C_{ox})}{1 + jwR_{seal}(C_M + C_{ox})}\right) \tag{8}$$

Hence the transfer function can be written as following:

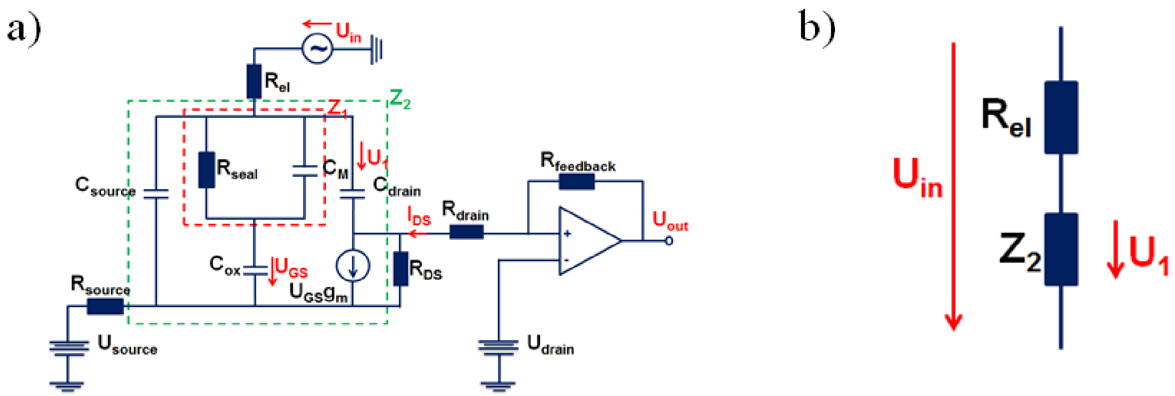
$$H(jw) = R_{feedback}g_m\frac{U_1(jw)}{U_{in}(jw)}\left(\frac{1 + jw\left(R_{seal}C_M - \frac{C_{drain}}{g_m}\right) + w^2R_{seal}\frac{C_{drain}}{g_m}(C_M + C_{ox})}{1 + jwR_{seal}(C_M + C_{ox})}\right) \tag{9}$$

The input voltage U_{in} can be calculated by a voltage divider (Figure 4Sb):

$$\frac{U_{in}(jw)}{R_{el} + Z_2} = \frac{U_1(jw)}{Z_2} \qquad (10),$$

where Z_2 is the impedance of the elements connected in parallel namely source contact line capacitance C_{source}, the drain contact line capacitance C_{drain} and the impedance consisting of the impedance Z_1 and the gate oxide capacitance in series (Figure 4Sa).

Figure 4S. (a) The elements namely source contact line capacitance C_{source},, the drain contact line capacitance C_{drain} and the impedance consisting of the impedance Z_1 and the gate oxide capacitance C_{ox} in series can be combined to one impedance Z_2 across these the same voltage U_1 drops. (b) A voltage divider consisting of the resistance R_{el} and the impedance Z_2



$$\frac{1}{Z_2} = jw(C_{source} + C_{drain}) + \frac{jwC_{ox}(1 + jwR_{seal}C_M)}{1 + jwR_{seal}(C_M + C_{ox})} \qquad (11)$$

$$Z_2 = \frac{1 + jwR_{seal}(C_M + C_{ox})}{jw(C_L + C_{ox}) - w^2R_{seal}(C_L(C_M + C_{ox}) + C_MC_{ox})}$$

(12),

where the capacitances of the contact lines can be combined to $C_L=C_{source}+C_{drain}$

$$Z = R_{el} + Z_2 = \frac{1 + jw\left(R_{el}((C_L + C_{ox})) + R_{seal}(C_M + C_{ox})\right) - w^2R_{el}R_{seal}(C_L(C_M + C_{ox}) + C_MC_{ox})}{jw(C_L + C_{ox}) - w^2R_{seal}(C_L(C_M + C_{ox}) + C_MC_{ox})}$$

(13)

From this it follows that:

$$\frac{U_1(jw)}{U_{in}(jw)} = \frac{Z_2}{Z} = \frac{1 + jwR_{seal}(C_M + C_{ox})}{1 + jw\left(R_{el}\left((C_s + C_d + C_{ox})\right) + R_{seal}(C_M + C_{ox})\right) - w^2 R_{el}R_{seal}\left((C_s + C_d)(C_M + C_{ox}) + C_M \right.}$$

(14)

Finally, we need to consider the low pass characteristics of the first amplifier stage.

The equation (14) can be included into equation (8), which results in an analytical solution for the TTF-spectra of a single cell in contact to an FET sensor:

$$H(jw) = R_{feedback}g_m \frac{1 + jw\left(R_{seal}C_M - \frac{C_d}{g_m}\right) - w^2 R_{seal}C_d(C_M + C_{ox})}{1 + jw\left(R_{el}\left((C_L + C_{ox})\right) + R_{seal}(C_M + C_{ox})\right) - w^2 R_{el}R_{seal}\left(C_L(C_M + C_{ox}) + C_M C_{ox}\right)}$$

(15),

where f_g is the cutoff frequency of the operational amplifier, which takes the low pass effect of the transimpedance amplifier into account. This equation can now be used to fit the resulting TFF spectra in our experiments and to extract the adhesion-related data R_{seal} and C_M out of these spectra.