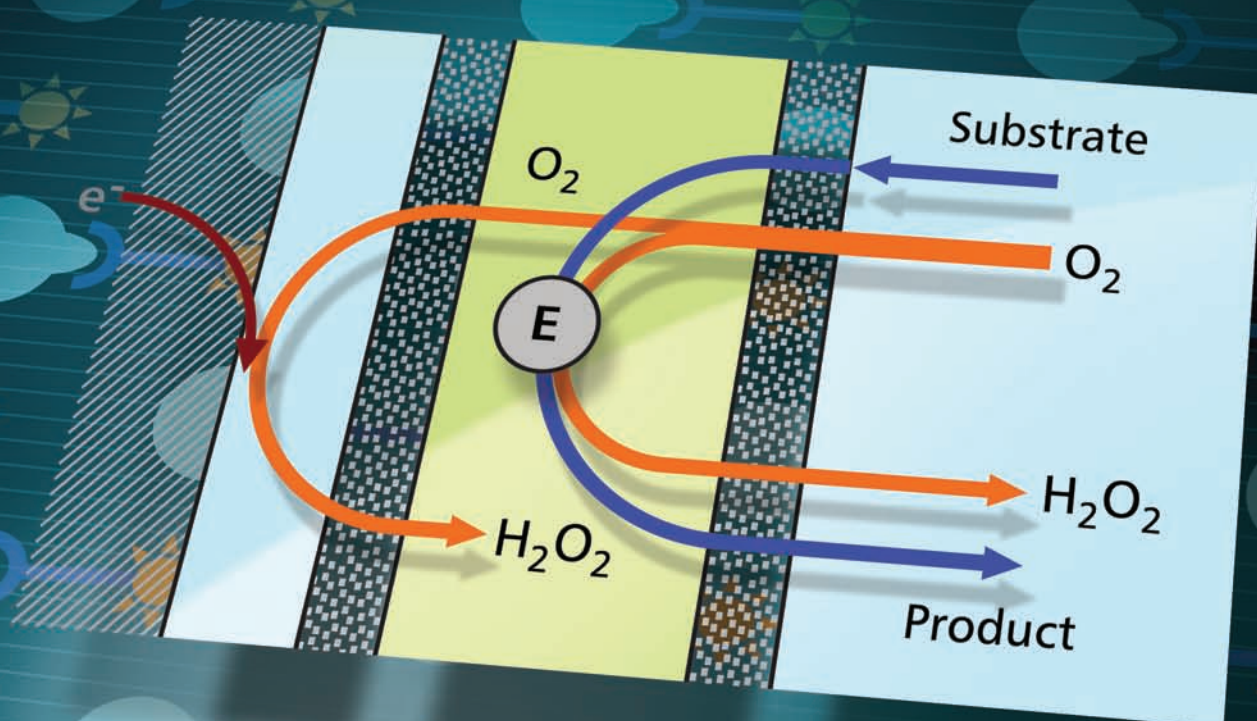


# Chemical Sensors and Biosensors

Fundamentals and Applications



Florinel-Gabriel Bănică



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## *Fundamentals and Applications*

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# Preface

As suggested by Marshal McLuhan, media (in the more general meaning of the term) act as extensions of the functions of the human body [1]. In the same way that the microphone acts as an extension of the ear, chemical sensors can be considered to be extensions of the organs of chemical perception that are the nose and the tongue.

The development of chemical sensors responds to the increasing demand of chemical data that characterize various systems of interest. Such a system can be the human body itself, whose physiological state can be assessed unequivocally by physical, chemical and biochemical parameters. The quality of the ambient and natural environment is characterized by measuring the content of noxious chemical species. No less important is the automatic control of certain industrial processes that depend on specific chemical parameters.

In general, standard analytical methods (e.g., chromatography, spectrometry and electrophoresis) can provide the same kind of information as that produced by chemical sensors. The advantage of the chemical sensor approach results from the fact that they are specialized, small size, portable and inexpensive devices that are suitable for *in situ* analysis and real-time monitoring of chemical parameters. Worthy of mention is the capability of dedicated chemical sensors to identify pathogen micro-organisms and viruses via characteristic compounds that are parts of the structure of the target species.

“There’s plenty of room at the bottom” said Richard Feynman in a seminal lecture in 1959, that anticipated the advent of nanotechnology. This sentence can be paraphrased as follows: “There’s plenty of new opportunities at the bottom”. This applies well to the development of chemical sensors. Indeed, the most important trend in this area is the application of nanomaterials, either as substitutes for classical materials and reagents or in the implementation of completely new sensing and transduction methods. Of outstanding importance is the size compatibility of nanomaterials with biopolymer molecules, which allows fabrication of bionanocomposites with promising potential for application in the design of chemical sensors. New fabrication technologies, mostly inspired by microelectronic technology and nanotechnology, are expected to lead to an increase in the degree of integration in chemical-sensor arrays, thus prompting advances in production and application of artificial nose/tongue devices. Integration of chemical sensors with microfluidic systems is another promising trend since microfluidic systems allow extremely small sample volumes to be processed and analyzed automatically.

New books on chemical sensors are published regularly, but most of them are collective volumes profiling particular kinds of chemical sensor and particular applications of chemical sensors. A comprehensive overview of chemical sensors in one single book is needed for two reasons. First, such a book would serve as a useful teaching aid for use in courses covering the subject of chemical sensors. Secondly, an indepth introduction to the field of chemical sensors for scientists and engineers new to this subject would be advantageous. There are currently on the market a series of volumes that are intended to respond to the above aims. However, as the field progresses, a new book that covers recent advances is always welcome.

The development of a chemical sensor is very often a matter of material synthesis and processing. Synthetic materials (both inorganic and organic), materials of biological origin (proteins, nucleic acids, micro-organism and living cells), as well as biomimetic synthetic materials are widely used in the development of chemical sensors. Of equal importance is the fabrication technology, because the final goal in chemical-sensor research is the production of a marketable product. That is why the first eight chapters in this text introduce the main kinds of material used in the development of the chemical sensors, as well as typical processes and technologies involved in fabrication of chemical sensors. The next fourteen chapters present various classes of chemical sensors organized according to the transduction method. The final chapter is devoted to chemical sensors based on highly organized biological material such as micro-organisms and living cells.

This book has been designed mostly as an instruction manual in chemical sensors, with a particular attention on balancing classical topics with contemporary trends. Clearly, owing to its extent, the contents of this book cannot be covered in a normal course of lectures. However, the course instructor can select topics that fit the class level and the particular interest of the attending students. Moreover, the curriculum can be personalized by encouraging each student to explore more deeply into certain advanced topics. In addition, a study of chemical sensors is an enlightening excursion through various scientific and technological areas, thereby contributing substantially to the development of the student’s scientific knowledge.

Additionally, this book will be useful to any scientist who needs an introduction into the field of chemical-sensor science and technology. As this is an interdisciplinary field, this book will be of interest to engineers, chemists, biochemists, microbiologists and physicists endeavoring to start up research work in the field of chemical sensors.

Nothing done by humans can be perfect, but, at least, it could be perfectible. Hence, any critical comment or suggestion is welcome.

1. McLuhan, M. (2003) *Understanding Media: The Extensions of Man*, Gingko Press, Corte Madera, Calif.

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Finally, I am grateful, in writing this book, to all those scientists who have contributed to the advance of chemical sensor science and technology. Many of these scientists are cited in the book, but, owing to space limitations, much valuable work in this area could not be included or cited.





# List of Symbols

## Roman Symbols

Symbol	Meaning	Section Reference
$A$	(a) surface area (b) absorbance (c) amplitude of an electromagnetic wave	4.2.2; 13.3.1 18.3.1 18.6.2
$_{AC}$	subscript pertaining to alternating current	
$a$	(a) thermodynamic activity (b) sensor sensitivity (c) molar absorptivity (d) the exponent in the expression of CPE impedance	10.2.1 1.5 18.3.1 17.2.1
$b$	thickness of a light-absorbing layer	18.3.1
bipy	2,2'-bipyridine	
$C$	capacitance	11.1.3
$C_{dl}$	capacitance of the electric double layer	17.2.2
$C_f$	proportionality constant in the Sauerbrey equation	21.2.3
$C_0$	static capacitance in the equivalent circuit of a TSM oscillator	21.2.2
$C_1$	capacitance at the motional branch of the equivalent circuit of a TSM piezoelectric oscillator	21.2.2
$c$	(a) analyte concentration (b) concentration of the enzyme–substrate complex (c) concentration of the antibody–antigen complex (d) light velocity in vacuum	1.5 3.6.1 6.4 18.1
$c^*$	concentration of an excited-state species	18.3.6
$c_A$	concentration of the species A	10.4.2
$c_{AR}$	concentration of the analyte–receptor combination	18.4.1
$c_B$	concentration of the species B	10.4.2
$c_{O,b}$	concentration of the oxidized form of a redox couple in the bulk solution	11.3.1
$c_{O,i}$	concentration of the oxidized form of a redox couple at the electrode/electrolyte interface	11.3.1
$c_Q$	concentration of a fluorescence quencher	18.3.7
$c_R$	receptor concentration	18.4.1
$c_{R,t}$	total concentration of the receptor	18.4.1
$c_{R,b}$	concentration of the reduced form of a redox couple in the bulk solution	11.3.1
$c_{R,i}$	concentration of the reduced form of a redox couple at the electrode/electrolyte interface	11.3.1
$D$	diffusion coefficient	4.2.2; 13.3.1
$Da$	Damköhler number for internal diffusion in an immobilized enzyme layer	4.3.1
$Da_M$	mediator Damköhler number	15.2.2
$Da_S$	substrate Damköhler number	15.2.2
$_{DC}$	subscript pertaining to direct current	
$D_M$	diffusion coefficient of a redox mediator	15.2.1
$D_{P,e}$	diffusion coefficient of the product within an immobilized enzyme layer	4.3.1
$D_{P,m}$	diffusion coefficient of the product in the external membrane of an enzymatic sensor	4.2.2
$D_{S,e}$	diffusion coefficient of the substrate within an immobilized enzyme layer	4.3.1
$D_{S,m}$	diffusion coefficient of the substrate in the external membrane of an enzymatic sensor	4.2.2
$E$	enzyme	3.6.1
$E$	(a) energy (b) electrode potential (b) Young modulus	11.1.2 10.2.2; 13.3.1 22.1.2

$\Delta E$	difference between the actual electrode potential and the formal electrode potential	13.6.1
$E_{\text{cell}}$	cell voltage	10.2.2
$E_{\text{AC}}$	sine wave alternating potential	13.7.7
$E_{\text{F}}$	Fermi energy	11.1.2
EMF	electromotive force	10.2.2
$E_{\text{ph}}$	photon energy	18.1
$E_{\text{pzc}}$	potential of zero-charge	13.5.2
$E_{\text{O}}$	oxidase enzyme in the oxidized form	14.2.1
$E_{\text{r}}$	reference electrode potential	10.4.1
$E_{\text{R}}$	oxidase enzyme in the reduced form	14.2.1
ES	enzyme–substrate complex	3.6.1
$E_{1/2}$	half-wave potential	13.3.2
$E^0$	standard electrode potential	10.2.2
$E_{\text{f}}^0$	formal electrode potential	10.2.2; 13.3.1
$E_0$	prelogarithm constant in the response equation of a potentiometric ion sensor	10.4.1
$e$	(a) enzyme concentration	3.6.1
	(b) elementary charge	11.1.3
	(c) the base of natural logarithm	17.1
$e_{\text{O}}$	concentration of the oxidized form of an oxidase enzyme in an immobilized enzyme layer	15.1.1
$e_{\text{R}}$	concentration of the reduced form of an oxidase enzyme in an immobilized enzyme layer	15.1.1
$e_{\text{t}}$	total enzyme concentration	3.6.1
$e_y$	measurement error of the sensor response	1.5
$e^-$	electron	
$F$	(a) Faraday constant	
	(b) power of a fluorescence light beam	18.3.5
$F_0$	fluorescence power in the absence of a quencher	18.3.7
$f$	(a) $F/RT$	13.6.1
	(b) frequency	13.7.7; 21.2.2
$f_e$	enzyme loading factor	4.3.1
$\Delta f_{\text{L}}$	change in the resonance frequency due to liquid loading on a TSM piezoelectric resonator	21.2.5
$\Delta f_{\text{m}}$	change in the resonance frequency due to mass loading	21.2.3
$f_{\text{O}}$	(a) $m_{\text{O}}/m_{\text{t}}$	15.1.1
	(b) $m_{\text{O},0}/m_{\text{t}}$	15.2.3
$\tilde{f}$	complex frequency of a TSM resonator	21.2.7
$f_0$	resonant frequency of an oscillator	21.2.1; 22.1.3
$G$	Gibbs free energy	10.2.1
$\Delta G$	Gibbs free energy change in a chemical process	10.2.2
$\Delta G^*$	activation energy of a chemical reaction	13.6.1
$\Delta G^0$	standard Gibbs free energy change in a chemical process	10.2.2
$\text{GOD}_{\text{ox}}$	glucose oxidase, oxidized form	3.5.1
$\text{GOD}_{\text{red}}$	glucose oxidase, reduced form	3.5.1
$\Delta H$	heat of reaction	Chapter 9
$\Delta H_r^0$	standard enthalpy of reaction	Chapter 9
$h$	(a) Plank's constant	18.1
	(b) microcantilever thickness	22.1.1
$I$	(a) ionic strength	10.2.1
	(b) electric current	17.1
$I_{\text{AC}}$	sine-wave alternating current	17.1
$I_{\text{D}}$	drain current of a metal-insulator-semiconductor field effect transistor	11.1.4
$I_{\text{DC}}$	DC current	17.1
$I_{\text{m}}$	AC current amplitude	17.1
$i$	electrolytic current	13.3.1
$i_{\text{a}}$	anodic current	13.3.1
$i_{\text{a,d}}$	limiting, diffusion-controlled anodic current	13.3.2
$i_{\text{C}}$	capacitive current	13.5.3
$i_{\text{c}}$	cathodic current	13.3.1
$i_{\text{c,d}}$	limiting, diffusion-controlled cathodic current	13.3.1

$i_f$	Faradaic current	13.7.7
$i_l$	limiting current at an mediator-based amperometric enzyme sensor	15.1.3
$i^*$	the particular value of the limiting current recorded at $\alpha \gg 1$ and for $S = 1$	15.1.3
$i_0$	exchange current	13.6.4
$J$	diffusion flux	
$J_d$	limiting flux under first order kinetics and external diffusion control	15.1.2
$J_l$	flux limiting value	15.1.2
$J_{l,0}$	flux limiting value under zero-order kinetics	15.1.2
$J_{l,1}$	flux limiting value under first-order kinetics	15.1.2
$J_M$	mediator flux	15.2.1
$J_P$	product flux in an enzymatic sensor	4.2.1
$J_S$	substrate flux in an enzymatic sensor	4.2.1
$J_{P,m}$	product flux in the membrane of an enzymatic sensor	4.4.1
$J_{S,m}$	substrate flux in the membrane of an enzymatic sensor	4.4.1
$J^*$	the particular value of $J_d$ for $s = K_M$	15.1.3
$j$	(a) current density (b) imaginary unit ( $\sqrt{-1}$ )	13.6.2 17.1; 21.2.2
$j_a$	anodic current density	13.6.2
$j_{a,d}$	limiting (diffusional) anodic current density	13.6.3
$j_c$	cathodic current density	13.6.2
$j_{c,d}$	limiting (diffusional) cathodic current density	13.6.3
$j_0$	exchange-current density	13.6.4
$K_a$	affinity constant	6.2.2
$K_d$	dissociation constant	18.4.1
$K_e$	equilibrium constant for the analyte–receptor interaction	18.4.1
$K_{ex}$	ion-exchange constant for a glass membrane	10.6.2
$K_{exch}$	ion-exchange constant for an ion-exchanger liquid membrane	10.8.3
$K_M$	Michaelis–Menten constant	3.6.1
$K_p$	partition coefficient	10.3.2
$K_{p,M}$	partition coefficient of the ion M	10.9.4
$K_s$	solubility constant of a sparingly soluble salt	10.5.2
$k$	spring constant of the microcantilever material	22.1.3
$k_a$	surface normalized pseudo-first-order rate constant for an enzymatic sensor	4.2.4
$k_{A,B}^{pot}$	potentiometric selectivity coefficient relative to ions A and B	10.4.2
$k_B$	Boltzmann constant	11.1.2
$k_{cat}$	turnover number of an enzyme	3.6.3
$k_d$	decay rate constant of an excited state species	18.3.6
$k_e$	(a) pseudo-first-order reaction rate for an enzyme-catalyzed reaction (b) excitation rate constant	6.2.2 18.3.7
$k_H$	proportionality coefficient in the Henry isotherm	11.3.5
$k_m$	mass-transfer coefficient	13.3.1
$k'_M$	reaction rate for enzyme regeneration by reaction with a redox mediator	15.1.1
$k_{M,N}^{pot}$	potentiometric selectivity coefficient relative to ions M and N	10.6.2
$k_{m,P}$	mass-transfer coefficient of the product	4.2.2
$k_{m,S}$	mass-transfer coefficient of the substrate	4.2.2
$k_{P,m}$	mass-transfer coefficients of the product in the membrane of an enzymatic sensor	4.4.1
$k_s$	standard rate constant of an electrochemical reaction	13.6.1
$k_{S,m}$	mass-transfer coefficients of the substrate in the membrane of an enzymatic sensor	4.4.1; 15.1.1
$k_{SV}$	Stern–Volmer constant	18.3.7
$k_1$	forward rate constant of the first step in the Michaelis–Menten mechanism	3.6.1
$k_{-1}$	backward rate constant of the first step in the Michaelis–Menten mechanism	3.6.1
$k_2$	rate constant for the second step in the Michaelis–Menten mechanism	3.6.1
$L$	(a) luminophores species (b) analyte-analog	18.3.7 18.4.2
$L$	electrical conductance	17.8.1
$L^*$	excited luminophores species	18.3.7
$L_1$	inductance at the motional branch of the equivalent circuit of a TSM piezoelectric oscillator	21.2.2
$l$	(a) distance between the plates of a capacitor (b) distance between the electrodes of an idealized conductometric cell (c) microcantilever length	13.5.3 17.8.1 22.1.1

$l_e$	thickness of an immobilized enzyme layer	4.2.1; 15.1.2
$l_m$	thickness of the external membrane in an enzymatic sensor	4.2.1
$M_O$	oxidized form of a redox mediator	14.2.1
$M_R$	reduced form of a redox mediator	14.2.1
$m$	(a) activity of an unspecified $M^+$ ion	10.5.2
	(b) mass	22.1.3
$\Delta m$	mass variation	21.2.3; 22.1.3
$m^*$	effective mass of a vibrating microcantilever	22.1.3
$m_{aq}$	activity of an unspecified $M^+$ ion in solution	10.3.2
$m_m$	activity of an unspecified $M^+$ ion in an ion-selective membrane	10.3.2
$m_O$	concentration of the oxidized form of a redox mediator	15.1.1
$m_{O,0}$	concentration of the oxidized mediator at the electrode surface	15.2.3
$m_Q$	mass of the vibrating zone of a TSM piezoelectric oscillator	21.2.3
$m_R$	concentration of the reduced form of a redox mediator	15.1.1
$m_{R,0}$	concentration of the reduced mediator form at the electrode surface	15.2.3
$m_t$	$m_O + m_R$	15.1.1
$m_1$	activity of an unspecified $M^+$ ion within the left-hand solution of an ion-selective membrane cell	10.5.2
$m_2$	activity of an unspecified $M^+$ ion within right-hand solution of an ion-selective membrane cell	10.5.2
$N_O$	number of moles of oxidized form of a redox couple	13.3.1
$N_R$	number of moles of reduced form of a redox couple	13.3.1
$n$	(a) number of moles	10.2.1
	(b) number of electrons in an electrochemical reaction	10.2.2; 13.3.1
	(c) activity of an unspecified $N^+$ ion	10.5.2
	(d) refractive index	18.2.1
	(e) overtone order	21.2.1
$n_0$	refractive index of the medium from which a light beam comes to an optical fiber	18.2.1
$n_1$	refractive index of the waveguide core	18.2.1
$n_2$	refractive index of the waveguide cladding	18.2.1
$n_{eff}$	effective refractive index	18.6.2
$Ox$	oxidized form of a redox couple	10.2.2; 13.3.1
$o$	subscript denoting quantities pertaining to the oxidized form of a redox couple	10.2.2; 13.3.1
$P$	reaction product	3.6.1
$P$	power of the transmitted light beam	18.3.1
$P_e$	dimensionless concentration of the reaction product in an immobilized enzyme layer ( $p_e/K_M$ )	4.2.5
$P_0$	power of the reference light beam	18.3.1
$p$	(a) concentration of a reaction product	4.2.1
	(b) partial pressure	10.2.2
$p_e$	concentration of the reaction product within an immobilized enzyme layer	4.2.1
$p_{e,0}$	concentration of the product at the transducer/immobilized enzyme layer interface	4.3.1
$p_{CO_2}$	partial pressure of carbon dioxide	10.17.4
$pH$	the negative logarithm (base 10) of hydrogen ion activity	
$p_{H_2}$	partial pressure of hydrogen	11.3.1
$p_{O_2}$	partial pressure of oxygen	10.17.2
$p_{m,i}$	product concentration at the membrane-enzyme layer interface	4.4.1
$Q$	(a) electrical charge	
	(b) quality factor of a resonator	21.2.7; 22.1.3
$QY$	fluorescence quantum yield	18.3.4
$R$	recognition receptor	
$R$	(a) ideal gas constant	
	(b) electrical resistance	9.1.1; 17.2.2
	(c) reflected light power	18.3.2
$R$	subscript pertaining to the reduced form of a redox couple	10.2.2; 13.3.1
$R_{Air}$	electrical resistance of a resistive gas sensor in contact with pure air	12.2.2
$Red$	reduced form of a redox couple	10.2.2; 13.3.1
$R_{et}$	electron-transfer resistance	13.6.5; 17.2.3
$R_{Gas}$	electrical resistance of a resistive gas sensor in contact with analyte-containing gas	12.2.2
$R_{ref}$	resistance of a resistive gas sensor in contact with a reference gas	12.2.2

RH	relative humidity	17.9.1
$R_S$	electrical resistance of a resistive gas sensor	12.2.2
$R_s$	resistance of an electrolyte solution	13.2; 17.2.1; 17.2.3
$R_1$	resistance at the motional branch of the equivalent circuit of a TSM piezoelectric oscillator	21.2.2
$r$	(a) radius (b) receptor concentration	6.4
$r_h$	relative humidity	17.9.1
$r_T$	the turnover number of the substrate conversion relative to that of the enzyme reoxidation	15.1.2
$r_0$	total receptor concentration	6.4
S	enzyme substrate	3.6.1
$S$	dimensionless concentration of the substrate ( $s/K_M$ )	15.1.3
$S_e$	dimensionless concentration of the substrate within an enzymatic layer under external diffusion control ( $s_e/K_M$ )	4.2.5
$s$	substrate concentration	3.6.1
$s_e$	substrate concentration in an enzymatic layer	4.2.1; 15.1.1
$s_{e,0}$	substrate concentration at the transducer/immobilized enzyme layer interface	4.3.1
$s_{m,i}$	substrate concentration at the membrane/enzyme layer interface	4.4.1
$T$	(a) absolute temperature (b) transmittance	18.3.1
$T_d$	dew point	17.9.1
$T_{xy}$	shear stress	21.2.4
$t$	time	
$\Delta t$	change in the thickness of a TSM piezoelectric oscillator	21.2.3
$t_Q$	thickness of a TSM piezoelectric oscillator	21.2.1
$t_r$	response time	4.3.2
$u$	ion mobility	10.3.1
$V$	(a) voltage (b) volume of an enzyme layer	4.2.2
$V_{AC}$	sine wave alternating voltage	7.1
$V_D$	drain voltage for a metal-insulator-semiconductor field effect transistor	11.1.4
$V_{DC}$	DC voltage	17.1
$V_G$	gate voltage for a metal-insulator-semiconductor field effect transistor	11.1.4
$V_{FB}$	flat-band voltage	11.1.3
$V_m$	amplitude of sine-wave alternating voltage	17.1
$V_T$	threshold voltage of a metal-insulator-semiconductor device	11.1.3
$V_T^*$	threshold voltage of an electrolyte-insulator-semiconductor device	11.2.1
$v$	(a) velocity (b) potential scan rate (c) reaction rate	21.2.4 13.7.4 3.6.1
$v'$	reaction rate within an immobilized enzyme layer	4.2.2
$v_a$	surface-normalized reaction rate in an enzymatic sensor	4.2.2
$v_e$	reaction rate of an electrochemical reaction	13.3.1
$v_{e,a}$	velocity of an anodic reaction	13.6.1
$v_{e,c}$	velocity of a cathodic reaction	13.6.1
$v_M$	reaction rate of enzyme regeneration	15.1.1
$v_m$	maximum reaction rate of an enzyme-catalyzed reaction	3.6.1
$v_S$	reaction rate for the formation of an enzyme-substrate complex	15.1.1
$v_{tr}$	propagation velocity of a transverse wave	21.2.3
$v_V$	volume reaction rate within an immobilized enzyme layer	4.2.2
$v_x$	velocity along the $x$ -axis	21.2.7
$v_C$	reaction rate of the substrate conversion in an enzyme-substrate complex	15.1.1
$w$	microcantilever width	22.1.1
$X_C$	capacitive reactance ( $1/\omega C$ )	21.2.2
$X_L$	inductive reactance ( $\omega L$ )	21.2.2
$x$	distance	
$\Delta x$	microcantilever deflection	22.1.2
$Y$	admittance	17.1

$Y_t$	total admittance	17.1
$y$	response signal of a sensor	1.5
$z$	ion charge	10.2.1
$Z$	(a) electrical impedance	17.1
	(b) acoustic impedance	21.2.7
$ Z $	impedance modulus	17.1
$Z'$	real part of the acoustic impedance of a TSM piezoelectric oscillator	21.2.2
$Z''$	imaginary part of the acoustic impedance of a TSM piezoelectric oscillator	21.2.2
$Z_C$	capacitive impedance	17.2.1
$Z_F$	Faradaic impedance	17.2.3
$Z_{im}$	imaginary part of electrical impedance	17.1
$Z_m$	motional impedance	21.2.7
$Z_{m1}$	motional impedance of an unloaded TSM piezoelectric resonator	21.2.2
$Z_{m2}$	motional impedance produced by loading a TSM piezoelectric resonator	21.2.7
$Z_{m,t}$	total motional impedance	21.2.7
$Z_{re}$	real part of electrical impedance	17.1
$Z_s$	mechanical impedance of a TSM resonator	21.2.7
$Z_t$	total impedance	17.1
$Z_W$	Warburg impedance	17.2.1

## Greek Symbols

Symbol	Meaning	Section References
$\alpha$	(a) substrate modulus for an enzymatic sensor under external diffusion control	4.2.4
	(b) transfer coefficient of a cathodic electrochemical reaction	13.3.3
$\beta$	(a) Biot number	4.4.1
	(b) transfer coefficient of an anodic electrochemical reaction	13.6.1
$\Gamma$	surface concentration	5.2
$\Gamma_{max}$	maximum surface concentration	5.2
$\gamma$	(a) activity coefficient	10.2.1
	(b) enzyme reoxidation capacity relative to the substrate conversion capacity in the absence of any diffusion limitation	15.2.2
$\delta$	(a) thickness of the Nernst diffusion layer	13.3.1
	(b) charge fraction transferred in the interaction of a polar molecule with a semiconductor	11.3.5
	(c) Debye length	12.1.7
$\delta_{dl}$	thickness of the electrical double layer	17.2.2
$\delta_S$	partition coefficient of the substrate	4.4.1
$\delta_P$	partition coefficient of the product	4.4.1
$\epsilon_d$	dielectric constant	13.5.2
$\epsilon_{dl}$	dielectric constant within the electrical double layer	17.2.2
$\eta$	(a) $Da_M/Da_S$	15.2.2
	(b) overvoltage (difference between the actual electrode potential and the equilibrium potential)	13.6.5
	(c) dynamic viscosity	21.2.4
$\eta_L$	dynamic viscosity of a liquid	21.2.5
$\theta$	surface coverage degree	5.2
$\theta_e$	internal lag factor	4.4.1
$\theta_c$	critical incidence angle	18.2.1
$\theta_m$	external lag factor	4.4.1
$\theta_1$	incidence angle	18.2.1
$\theta_2$	refraction angle	18.2.1
$\Lambda$	molar conductivity	17.8.1
$\Lambda_i$	molar conductivity of an ion $i$	17.8.1