The ammonia sensitivity of Pt/GaAs Schottky barrier diodes

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In this work a new ammonia gas sensor is presented. Schottky barrier devices, Pt/*n*-GaAs, with discontinuous platinum films are sensitive detectors of ammonia gas in a wide temperature range (from room temperature to 150 °C). The effect of parameters such as operation temperature, thickness of the catalytic metal film, background atmosphere, and applied voltage bias on the device sensitivity are investigated. In addition, significant characteristics have been examined including sensitivity limits, linearity of response, and adsorption and desorption kinetics.

I. INTRODUCTION

The determination of ammonia gas concentration is important in clinical, industrial process analysis, and environmental protection. For these reasons, it is useful to fabricate an ammonia sensor of small size, low cost, and high sensitivity.

Ammonia-sensitive structures based on metal-oxide-semiconductor (MOS) and metal-oxide-semiconductor field-effect transistor (MOSFET) devices with thin catalytic metal films have been reported.¹⁻³ Two models have been proposed to explain the NH₃ sensitivity of the thin catalytic gate device. It was first proposed that NH₃ dissociated to yield atomic hydrogen, which diffuses to the metal-oxide interface to give a dipole layer. This changes the electrical characteristics of the device in a similar way as for hydrogen sensors.⁴ Later, Lundström and co-workers developed a model to explain NH₃ sensitivity based on a capacitive coupling of ammonia molecules and/or reaction intermediates with the semiconductor through pores in the metal film.⁵

Schottky barrier devices have been shown to be excellent H₂ gas sensors^{6,7} with high sensitivity and a behavior similar to MOS or MOSFET H₂ gas sensors.⁸⁻¹⁰ In this work we present a new ammonia gas sensor based on a Pt/*n*-GaAs Schottky barrier diode. The sensitivity of the sensor is given by the increase in capacitance observed when the NH₃ gas reaches the structure. The change in capacitance is, therefore, a measurement of the amount of ammonia molecules in the ambient. We have carried out reaction kinetics studies via capacitance-time measurements as a function of temperature and NH₃ concentration in different background atmospheres.

II. EXPERIMENT

The diodes were fabricated on (100) Si-doped GaAs epilayers (donor concentration, $N_d = 4 \times 10^{15} \text{ cm}^{-3}$), grown by molecular-beam epitaxy on a GaAs substrate. The devices have a dual metallic configuration: a thick (500-Å) Pt circular dot (diameter = 1 mm) for an electric contact is first deposited. A thin porous Pt film (25–200 Å thickness) is evaporated over and outside the contact dot. Pt was electron-beam evaporated in an ultrahigh vacuum system at 10^{-7} Torr through a mask. Back ohmic contact

on the *n*-type GaAs substrate is made previously by Au-Ge thermal evaporation with a subsequent annealing in H₂ at 450 °C for 30 s. A quartz-crystal oscillator was used to estimate the thickness of the metal film. The diodes fabricated had an ideality factor close to unity. A schematic cross section of a NH₃ sensor can be seen in Fig. 1.

Devices were located in a stainless-steel reaction chamber connected to a gas-flow panel which controlled the ambient atmosphere. Measurements were carried out in different gas mixtures: NH₃ in N₂ and NH₃ in synthetic air (20% O₂ in N₂); high-purity gases were used (moisture <5 ppm). All of the measurements were made at atmospheric pressure.

Gas-induced modifications in Schottky diode electrical properties are quantified by measuring changes in the diode capacitance as a function of time, as shown in Fig. 2. We have examined the effects of several parameters like temperature, voltage bias, and gaseous ambient. High-frequency (1-MHz) capacitance-voltage (*C-V*) and capacitance-time (*C-t*) measurements were obtained with a Hewlett-Packard 4280A capacitance meter.

III. RESULTS AND DISCUSSION

A. Influence of different parameters

1. Metal thickness, voltage bias, and temperature

The metal microstructure strongly affects the NH₃ sensitivity of sensors based on MOSFET devices² with thin catalytic metal gates. We have studied a platinum film thickness range between 25 and 200 Å. The devices did not show any sensitivity when the film was thicker than 150 Å, as shown in Fig. 3(a). In Fig. 3(b) we present measurements carried out in diodes with a platinum thickness of 25 and 75 Å, at 150 °C, and zero-voltage bias, in the presence of 75–300 ppm of ammonia. Normalized signals are used to compare the response of different diodes. The lack of ammonia sensitivity when the film becomes continuous indicates that the NH₃ detection mechanism is different from the H₂ detection mechanism.

The porous structure of the film has been observed by scanning electron microscopy (SEM) and scanning tunneling microscopy (STM). SEM and STM microphotographs show that the metal film has pores, although the film is electrically continuous.

FIG. 1. Schematic cross section of an ammonia sensor. Pt dot thickness is 500 Å. Porous layer thickness is between 25 and 75 Å.

Figure 4(a) shows capacitance change for 970 ppm of ammonia in nitrogen gas, at 150 °C, as a function of time for several bias voltages. Zero-voltage bias gives the largest signal. Furthermore, total recovery of the signal is achieved at this voltage for 150 °C. Consequently, we have made the forthcoming measurements at zero-voltage bias.

Figure 4(b) shows how the sensitivity increases with temperature for 970 ppm of NH_3 gas in nitrogen. The devices show a small but measurable response to NH_3 even at room temperature, both in N_2 and synthetic air.

2. Background atmospheres

The role of different carrier gases has been studied. Measurements were carried out at 150 °C and zero-voltage bias. In all cases desorption was carried out in O_2/N_2 (50%) at 150 °C to achieve a complete desorption in about 2.5 min. The total desorption process in synthetic air (O_2/N_2 at 20%) takes about 5 min.

a. NH_3/N_2 . The response to NH_3 in N_2 was investigated with an ammonia concentration from 40 to 970 ppm.

FIG. 2. Typical response curve (capacitance vs time) of a NH_3 sensor. (C_0) initial capacitance; (ΔC) increase of capacitance, measured just before desorption; constant time (τ), time in which the capacitance reaches the value ($e^{-1} \Delta C + C_0$); ($\Delta C / \Delta t = \tan \alpha$) initial rate of adsorption (or desorption).

(a)

(b)

FIG. 3. (a) Dependence of the NH_3 sensitivity with the porous Pt layer thickness. Signal is measured as normalized capacitance. Measurements were carried out for 225 ppm NH_3 in N_2 at 150 °C and zero-voltage bias. (b) Sensitivity of the device as a function of NH_3 partial pressure with thickness as a parameter: (●) 25-Å Pt film thickness, (■) 75-Å Pt film thickness.

The signal amplitude (ΔC) had the same value, although differences in time response were observed.

In the first set of measurements, the devices were previously exposed to a pure N_2 atmosphere for 5–10 min before the introduction of NH_3 gas. The response curve depicted in Figs. 5(a) and 5(b) shows some features depending on the ammonia partial pressure range. At high concentration the signal goes down abruptly when NH_3/N_2 is introduced, and then rises to give the adsorption curve. The values of initial capacitance depend on the previous exposure time to N_2 gas. At low concentrations, Fig. 5(b), two regions are observed that are more evident for lower NH_3 concentrations.

In the second set of measurements, experiments were carried out in an initial O_2/N_2 (50%) atmosphere prior to introduction of NH_3/N_2 . Figure 6 presents the response curve. In this case, two regions are observed again for almost all of the ammonia partial pressure range. As the ammonia concentration decreases, the first signal increases, although the total signal is constant.

The first signal observed in Figs. 5(b) and 6 could be due to nitrogen gas adsorption. N_2 gas replace the sites occupied by oxygen. It is known that certain ambient gases

FIG. 4. Response curve of adsorption of 970 ppm NH_3 in N_2 : (a) voltage bias as a parameter at 150 °C, (b) temperature as a parameter at 0 V.

can affect electrical properties of thin metal film¹¹ and the heterogeneous catalytic activity of Pt in N_2 adsorption¹² has been established. In order to elucidate whether N_2 gas originates the observed adsorption, we carried out adsorption studies of N_2 gas, NH_3 in N_2 , and H_2 in N_2 . Figure 7 shows the adsorption curves at 150 °C and zero-voltage bias. Pure N_2 gas induced an adsorption curve which correlates in position and shape with the first adsorption observed in the response curves of H_2/N_2 and NH_3/N_2 . The first adsorption signal corresponding to the curves of NH_3/N_2 and H_2/N_2 is very similar to the nitrogen adsorption signal ($\Delta C = 9.0, 9.5$, and 11.0 pF, respectively). Notice the high sensitivity for H_2 in this type of device ($\Delta C = 9.7$ for NH_3 and 128 pF for H_2 , measured just before desorption), for the same gas concentration, and a similar response time.

FIG. 5. Response curves of NH_3 in N_2 , with a previous ambient of N_2 . Measurements were carried out at 150 °C and zero-voltage bias. (a) NH_3 concentration ranging between 970 and 360 ppm, (b) NH_3 concentration ranging between 230 and 40 ppm.

Adsorption of NH_3/N_2 and N_2 gas have been studied by means of C - V measurements. Plots of $1/C^2$ versus reverse voltage indicate that the Schottky barrier decreases when the gases are incorporated to the structure.

Plots of $1/C^2$ versus reverse voltage for the different atmospheres are shown in the Fig. 8. Comparing to the air

FIG. 6. Response curve of NH_3 in N_2 with a previous ambient of O_2 in N_2 (50%). NH_3 concentration ranges between 970 and 75 ppm. Measurements were carried out at 150 °C and zero-voltage bias.

FIG. 7. Response curves for the adsorption of 75 ppm of NH_3 in N_2 and 75 ppm of H_2 in N_2 and N_2 gas. Measurements were performed at 150°C and zero-voltage bias.

value [plot (a)], we obtain a Schottky barrier decreases of about 0.29 eV for 970 ppm of NH_3 in N_2 [plot (b)]. When 75 ppm of NH_3 in N_2 are introduced in the reaction chamber, we have calculated two different values corresponding to the two processes observed, the first process giving a lowering of about 0.07 eV [plot (c)], and the value corresponding to the second process is 0.20 eV (plot is not shown). Furthermore, when pure N_2 is introduced, we obtained a lowering of the Schottky barrier of 0.07 eV [plot (d)]. This result corroborates the idea that the first region is the adsorption signal corresponds to N_2 adsorption.

It is important to notice that, at temperatures below 75°C , the N_2 signal was not observed. At high tempera-

FIG. 8. $1/C^2$ vs reverse voltage for an ammonia sensor. (a) Sensor in synthetic air as a reference level. (b) Plot corresponding to the adsorption of 970 ppm of NH_3 in N_2 . (c) Plot corresponding to the first region observed in the adsorption curve of 75 ppm of NH_3 in N_2 . (d) Plot corresponding to N_2 gas adsorption.

(a)

(b)

FIG. 9. (a) Response curves of NH_3 diluted in synthetic air, measured at 150°C and zero-voltage bias. NH_3 concentration varies between 1000 and 10 ppm. ON = introduction of NH_3 . OFF = removal of NH_3 and introduction of O_2/N_2 (50%). Time between pulses is 250 s. (b) Response curves of adsorption of NH_3 in synthetic air corresponding to NH_3 pulses of 160, 80, and 10 ppm.

tures, nitrogen behaves as an interference for the NH_3 adsorption, although it is possible to differentiate both signals.

b. NH_3/air . The sensor was tested for ammonia in a synthetic air background atmosphere at 150°C and zero-voltage bias. Pulses of NH_3/air over a concentration ranging from 6 to 1200 ppm were injected into the reaction chamber with 250 s between pulses to ensure a total recovery of the sensor (purge time is 33 s). Figure 9(a) shows the on/off response curve of the device. In this case the N_2 adsorption process discussed above is not observed. Examples of the pulse responses are shown in Fig. 9(b). Such curves were recorded with a long time to evaluate the response time when the ammonia concentration decreases.

It is well known that the H_2 gas-sensitive devices show an abrupt lowering of response when oxygen is present.^{7,8} However, NH_3 sensitivity remains almost constant for different background atmospheres, NH_3 in N_2 or NH_3 in syn-

FIG. 10. Calibration graphs (constant time as a function of NH_3 concentration) of a device at different background atmosphere: (●) N_2 , (▲) synthetic air. Measurements were made at 150°C and zero-voltage bias.

thetic air. Therefore, the oxygen dependence of the ammonia response is different, and different rate-limiting reactions occur on the Pt surface for hydrogen and NH_3 exposure.

We have observed that the adsorption signal varies for the range of NH_3 partial pressures studied but this variation is small (only 7 pF for concentrations ranging between 1000 and 10 ppm). However, the time required for the signal to appear varies with the concentration of NH_3 , as can be seen in Fig. 9(b). The time needed for the capacitance change to reach e^{-1} of its final value was taken to be the time constant of the process (see Fig. 2). Figure 10 shows calibration plots of the time constant (τ) as a function of ammonia concentration for different background atmospheres. The calibration plots show the evaluation of NH_3 adsorption in N_2 (Fig. 6) and in synthetic air (Fig. 9). Time constants for NH_3 in N_2 have been evaluated with the initial value of capacitance referred to in the N_2 saturation level. As can be seen in Fig. 10, the time constant of the device is lower in air than in N_2 ambient in the whole range of NH_3 partial pressures studied. However, the slope of the NH_3/N_2 calibration plot is larger than that for the NH_3/air ambient, therefore, it is possible to better differentiate between close ammonia concentrations. In both cases, the calibration graphs are linear in the whole range of NH_3 concentrations studied in our experimental setup. The detection limit in N_2 is 10 ppm and decreases to 6 ppm in synthetic air.

As observed in Fig. 10, the response time is less than 1 min for NH_3 concentrations in air greater than 150 ppm. However, in N_2 ambient similar response times are obtained only when the NH_3 concentration is above 600 ppm.

B. Kinetics studies

The decomposition of NH_3 on polycrystalline Pt has been studied previously in an inert ambient.^{13,14} Nondisso-

ciative adsorption of ammonia occurs at temperatures below 160 K in an essentially nonactivated process. Other authors have found^{15,16} that the reaction for ammonia decomposition on platinum at higher temperatures is complex. Presumably, decomposition of NH_3 to NH_x takes place and the reaction rate is determined by the dissociation rate of the NH_x species.

Under the present experimental conditions one can expect NH_3 to be partly molecularly adsorbed and partly dissociatively chemisorbed on Pt. The fact that the adsorption signal increases with temperature supports the presence of some thermally activated dissociative chemisorption.

Kinetics studies were carried out by monitoring the capacitance of the device as a function of time and zero bias upon introduction and removal of N_2 and NH_3 in N_2 or in synthetic air. Reaction orders with respect to NH_3 were determined by examining the dependence of the initial rate of change of capacitance ($\tan \alpha$) during transients on ammonia partial pressure at a given temperature (see Fig. 2).

Reaction orders with respect to NH_3 have been estimated using different background atmospheres as shown in Fig. 11(a). A reaction order equal to one is calculated from the time evolution of the signal attributed to NH_3 adsorption in N_2 at 150°C . When synthetic air is used as carrier gas, the reaction order decreases to 0.5.

The corresponding desorption reaction orders have been calculated from the corresponding data in Fig. 11(a). Desorption was carried out in all cases at 150°C , zero voltage bias, and 50% O_2 in N_2 . Under these conditions, the zero-reaction order observed indicates that the desorption process is independent of NH_3 concentration, both in N_2 or in synthetic air, as can be seen in Fig. 11(a). Desorption of NH_3 in N_2 occurs faster than in synthetic air.

Examination of the dependence on temperature of the initial rate of change of capacitance during transients for a given gas-phase composition allowed for the determination of the activation energies associated with the process of NH_3 or N_2 introduction and removal from the Pt/GaAs structure.

The activation energy for NH_3 adsorption in N_2 has been evaluated in the temperature range between 100 and 150°C for two concentrations: 970 ppm (the first adsorption process is not observed) and 75 ppm (the first adsorption is observed). From the Arrhenius plot shown in Fig. 11(b), an activation energy of approximately 8 kcal/mol has been estimated for the higher concentration, attributed only to ammonia adsorption. For the lower concentration, two adsorption energies have been calculated. The first adsorption (curve N_2) gives a value of 15.3 kcal/mol and the second one (due to NH_3) gives a 7.5 kcal/mol value. This latter value is in good agreement with the previously obtained result for the higher NH_3 concentration.

Wilf and Dawson¹² studied the interaction of N_2 with polycrystalline Pt and observed dissociative nitrogen adsorption at room temperature. The rate of dissociation depended only on the time exposure, but not on the N_2 gas pressure. The energy necessary to break the dinitrogen

FIG. 11. (a) Dependence of initial signal change ($\Delta C/\Delta t$) on NH_3 partial pressure, at 150 °C and 0 V. (A) adsorption NH_3/N_2 , reaction order, $n = 1$; (B) adsorption NH_3 /synthetic air, $n = 0.5$; (C) first adsorption observed in NH_3/N_2 , $n = 0$; (A') desorption of (A), $n = 0$; (B') desorption of (B), $n = 0$. (b) Arrhenius plot for the adsorption of (in the 150–100 °C temperature range): (A) 970 ppm NH_3 in N_2 , $E_a = 8$ kcal/mol; (B) 34 ppm NH_3 in synthetic air, $E_a = 5.6$ kcal/mol; (C) 75 ppm NH_3 in N_2 , $E_a = 7.5$ kcal/mol; (D) N_2 gas, $E_a = 15.8$ kcal/mol; (E) first adsorption observed in the adsorption curve of 75 ppm NH_3 in N_2 , $E_a = 15.3$ kcal/mol. (c) Arrhenius plot for the desorption of (in the 150–100 °C temperature range): (A) 970 ppm NH_3 in N_2 , $E_a = 20.6$ kcal/mol; (B) 75 ppm NH_3 in N_2 , $E_a = 20.3$ kcal/mol; (C) N_2 gas only, $E_a = 19.9$ kcal/mol.

bond on the surface is easily compensated by the formation of the strong metal-nitrogen bonds. Adsorbed oxygen or sulfur inhibits nitrogen dissociative chemisorption mainly through a blocking of surfaces sites. This is probably the main reason why N_2 adsorption is not observed in an oxygen-containing ambient.

Heterogeneous catalysis studies have indicated that the

FIG. 12. (a) Schematic illustration of the proposed mechanism to explain the ammonia sensitivity of devices with porous Pt film. C_s = Schottky diode capacitance, C_c = coupling capacitance, and X = intermediate and/or reaction products of NH_3 decomposition. (b) Equivalent electrical circuit of (a).

dissociative adsorption of molecular nitrogen on Pt is an activated process with an activation energy approximately 16 kcal/mol.¹³ The chemisorption of dissociatively adsorbed N_2 was observed to occur above room temperature. The linearly bound N_2 molecule is the precursor for dissociation. Dinitrogen is bonded perpendicular to the metal surface through one N atom. Simultaneously with the dissociation of the N_2 bond, a bond between the N atom directed away from the surface and the metal is formed.

According to this, dissociative chemisorption of nitrogen takes place under the experimental conditions examined. We have been estimated an activation energy of 15.8 kcal/mol for nitrogen adsorption, in good agreement with above results, in the temperature range between 100 and 150 °C. This value is similar to that obtained for the first adsorption observed in the NH_3/N_2 adsorption process, in good agreement with the above discussion.

The situation is quite different with the presence of oxygen. Pt is known to be a good oxidation catalyst for NH_3 , and chemical reactions occur on the Pt surface at temperatures below 500 K. The reaction products are: H_2O , N_2 , nitric oxide (NO), and/or nitrous oxide (N_2O).^{17,18} An activation energy of 5.6 kcal/mol has been estimated for NH_3 adsorption in air between 100 and 150 °C for the adsorption of 34 ppm NH_3 in synthetic air from the plot shown in Fig. 11(b). This value of activation energy, 5.6 kcal/mol, compared to 8 kcal/mol for adsorption in N_2 ambient, correlates to the more rapid response achieved in the first case (see Fig. 10). This result is in good agreement with the fact that NH_3 adsorption takes place more rapidly in air.

Figure 11(c) shows the activation energy of the desorption processes for the same temperature range studied above. Very similar values have been obtained: 20.6 kcal/mol for the desorption of 970 ppm of NH_3/N_2 ; 20.3 kcal/mol for 75 ppm of NH_3 in N_2 ; and 19.9 kcal/mol for the desorption of N_2 gas.

Our experimental data could be explained by means of the model proposed by Lundström and co-workers.⁵ According to this author, ammonia molecules and/or reaction intermediates are capacitively coupled with the semiconductor through pores in the metal film. Based on this model, we propose the operation scheme shown in Fig. 12 for our Schottky barrier device.

NH_3 sensors based on a Pt/*n*-GaAs Schottky barrier

have a simpler design than their Si counterparts, which invariably require an intermediate insulator film to avoid a reaction between the metal and semiconductor.

The detection limit reported for NH_3 -sensitive MOS and MOSFET devices in air at 150°C is about 1 ppm of NH_3 .^{3,10} It was observed² that in certain cases both the speed of response and magnitude of the NH_3 -induced signal change during operation of the devices. Aging was found to be necessary for the NH_3 -sensitive Pt MOSFET reported by Ross and co-workers³ to reduce leakage and to improve device operating characteristics, and could be carried out by heating freshly prepared devices at 200°C for 48 h. However, the aging process is reversible and is an operating limitation with these devices. The response time (to 90% of equilibrium level) for the adsorption of 100 ppm of NH_3 in synthetic air was 3 min and for the recovery time is 10 min, with the total recovery taking about 45 min at 175°C .

We obtain a greater detection limit, about 6 ppm, determined by our experimental setup; the response time, for the same conditions, is 1 min. It is important to note that neither aging nor signal change during operation have been observed.

IV. CONCLUSIONS

We have found that Pt/GaAs devices with a discontinuous metal film are effective and reliable solid-state chemical sensors for the detection of ammonia gas. Devices operate over a wide temperature range and are sensitive even at room temperature. The diodes recover easily in air at 150°C . The ammonia sensitivity depends on the metal film microstructure. When the metal film is continuous, ammonia sensitivity disappears. Therefore, the NH_3 detection mechanism seems different from the H_2 operation mechanism.

The adsorption process of ammonia in nitrogen shows two adsorption curves. The first adsorption has been attributed to N_2 gas adsorption. This idea is confirmed by experimental results: pure N_2 produces an adsorption curve which correlates with the first adsorption observed. The lowering of the Schottky barrier due to N_2 gas adsorption coincides with the one produced by the first adsorption. Furthermore, the estimated activation energy for N_2 gas adsorption is similar to one obtained for the first adsorption observed in the NH_3/N_2 adsorption process. The nitrogen signal observed appears as an interference in our NH_3 response determination, although it is possible to differentiate both signals.

Ammonia adsorption in synthetic air is achieved without N_2 interference and with a faster response time than in the N_2 atmosphere. It is possible to measure NH_3 concentrations above 150 ppm with response times lower than 1

min. In a nitrogen ambient, fast response times (≈ 1 min) are only achieved for concentrations above 600 ppm. However, in a N_2 ambient signal sensitivity improves. The detection limit obtained with our experimental setup is of the order of 10 ppm of NH_3 in nitrogen or in synthetic air.

NH_3 gas is partly molecularly adsorbed and partly dissociatively chemisorbed on Pt. Adsorption rates vary proportionally to the ammonia concentration in the N_2 ambient. An activation energy of ≈ 8 kcal/mol is obtained for this process. When synthetic air is used as a carrier gas, the reaction order decreases to 0.5 and an activation energy of 5.6 kcal/mol is obtained. Therefore, the mechanisms for ammonia adsorption in N_2 and in synthetic air are different; different rate-limiting reactions occur on the Pt surface. The process is favored in synthetic air, as can be deduced from the activation energy values. Dissociative chemisorption of nitrogen gas occurs on the Pt surface, with an activation energy of ≈ 15.8 kcal/mol.

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- ¹I. Lundström, A. Spetz, F. Winquist, U. Ackelid, and H. Sundgren, *Sensors and Actuators B* **1**, 15 (1990).
- ²A. Spetz, M. Armgarth, and I. Lundström, *J. Appl. Phys.* **64**, 1274 (1988).
- ³J. F. Ross, I. Robins and B. C. Webb, *Sensors and Actuators* **11**, 73 (1987).
- ⁴F. Winquist, A. Spetz, M. Armgarth, C. Nylander, and I. Lundström, *Appl. Phys. Lett.* **43**, 839 (1983).
- ⁵I. Lundström, M. Armgarth, A. Spetz, and F. Winquist, in *Proceedings of the 2nd International Meeting on Chemical Sensors, Bordeaux, 1986*, edited by J. L. Aucouturier, J. S. Cauhapé, M. Destriau, P. Hagenmuller, C. Lucat, F. Ménil, J. Portier, and J. Salardenne (Bordeaux Chemical Sensors, Talence, France, 1986), p. 387.
- ⁶P. F. Ruths, S. Ashok, S. J. Fonash, and J. M. Ruths, *IEEE Trans. Electron Devices* **ED-28**, 1003 (1981).
- ⁷L. M. Lechuga, A. Calle, D. Golmayo, P. Tejedor, and F. Briones, *J. Electrochem. Soc.* **138**, 159 (1991).
- ⁸I. Lundström, *Sensors and Actuators* **1**, 403 (1981).
- ⁹T. L. Poteat, B. Lalevic, B. Kuliyeu, M. Yousuf, and M. Chen, *J. Electron. Mater.* **12**, 181 (1983).
- ¹⁰A. Spetz, M. Armgarth, and I. Lundström, *Sensors and Actuators* **11**, 349 (1987).
- ¹¹L. L. Kazmerski and D. M. Racine, *J. Appl. Phys.* **46**, 791 (1975).
- ¹²M. Wilf and P. T. Dawson, *Surf. Sci.* **60**, 561 (1976).
- ¹³J. J. Vajo, W. Tsai, and W. H. Weinberg, *J. Phys. Chem.* **89**, 3243 (1985).
- ¹⁴M. Grunze, in *The Chemical Physics of Solid Surfaces and Heterogeneous Catalysis*, edited by D. A. King and D. P. Woodruff (Elsevier, Amsterdam, 1982), Vol. 4, p. 143.
- ¹⁵J. L. Gland and E. B. Kollin, *J. Vac. Sci. Technol.* **18**, 604 (1981).
- ¹⁶B. A. Sexton and G. E. Mitchell, *Surf. Sci.* **99**, 523 (1980).
- ¹⁷T. Pignet and L. D. Schmidt, *J. Catal.* **40**, 212 (1975).
- ¹⁸J. L. Gland and J. N. Korchak, *J. Catal.* **53**, 9 (1978).