Chapter 4

Homogeneous Array Processing

Since most microelectronic chemical sensors are prone to a great deal of variation in process, drift, and mismatch, the output of a single sensor is often not particularly reliable. In order to improve the reliability of sensor data for subsequent signal processing, it is helpful to process a homogeneous array of individual sensors operating under identical conditions. Homogeneous processing converts the outputs from individual sensors into an aggregate output that is more robust and less noisy than any of the component inputs by minimizing the random components of the sensor signals caused by batch mismatch and drift variations. For example, a simple homogeneous processing step might involve the averaging of a cluster of sensor outputs. Averaging the outputs of M sensors operating at the same temperature produces a more robust output than a single sensor operating at that temperature, since many variations in the sensors themselves are random. Because random fluctuations in the final manufacturing process for chemical sensors, as for any mature manufacturing process, tend to be Gaussian in nature [50], mathematical averaging of a number of sensors subject to these random fluctuations produces an inherently more accurate output than that of an individual sensor. More systematic, non-gaussian variations such as drift and concentration changes are processed in subsequent signal processing centers through the normalization of heterogeneous arrays of sensor signals. These signal processing techniques are covered in detail in Chapter 5.

In addition to averaging, chemical sensor signals can be further preprocessed by eliminating the contribution of a broken sensor to an aggregate output. Depending on the technology on which they are based, chemical sensors can break either in an abnormally high or abnormally low state [43]; regardless of their failure mode, however, a broken sensor no longer provides relevant information about the sensing environment and therefore, should be eliminated from the computation of an average in the homogeneous processing stage. Because environmental poisoning of chemical sensors begins the moment they are exposed to air, broken sensors in these chemical sensing arrays are inevitable. Broken sensors are characterized in one of two ways. A broken sensor can produce an obviously erroneous output by generating an electrical open or short, thus mandating its removal as an outlier. A sensor output can also be analyzed in less obvious cases by standard statistical tests in order to determine whether or not its removal as an outlier is warranted. The setting of the outlier cutoff or limit is very dependent on the sensing technology itself and can vary from one technology to the next.

In this chapter, homogeneous processing techniques that involve the averaging of homogeneous sensory inputs and the elimination of outliers are presented. Each circuit is first described and then characterized with experimental results. An array of each type of circuit element is then tested in conjunction with an array of homogenous tin-oxide sensors operating at the same temperature and operating conditions in order to evaluate the effectiveness of processing on the homogeneous array. The outputs of these processing stages become the inputs to subsequent signal processing that will detect concentration and discriminate among chemicals.

4.1 Circuit Descriptions

In this section, four circuits are described. The first takes a simple average or mean of a homogeneous array of sensory inputs that have similar physical properties and operate at the same conditions. The second circuit removes low outliers from the mean computation and the third removes high outliers from the mean computation. Finally, the two outlier removal circuits are combined into a single dual outlier elimination element. The choice of which circuit to use is dependent on the failure modes of the sensing technology used in a particular chemical sensing system. These homogeneous processing circuits are specifically designed in analog VLSI for eventual integration with sensors on the chemical sensing plane to achieve the low cost and efficient communication goals established in previous chapters.

4.1.1 The Mean Detection Circuit

The mean, or mathematical average of a homogeneous cluster of sensors is often less noisy and more robust than the output of a single sensor. Inputs to a homogeneous cluster of sensors operating at a particular temperature, T_1, can be preprocessed together to produce an aggregate output,

$f(i_m)$, for subsequent signal processing that is simply the mathematical mean or average of the currents generated by the *M* sensor outputs as follows:

$$f_{T_1}(i_m) = \frac{1}{M} \sum_k i_k \tag{4.1}$$

where the *M* inputs, i_m, are all generated from sensors operating at the same temperature T_1. This mean output combined with others that correspond to the remaining operating temperatures in an array of sensors (T_2, T_3, T_n..... T_N) can be treated like a single sensor output and combined with similar aggregate outputs $(f_{T_2}(i_m), f_{T_3}(i_m), \ldots f_{T_N}(i_m))$ for subsequent signal processing. Ideally, the inputs to a homogeneous cluster would be the same; because of variations in the surface of these sensors caused by fabrication mismatch and process variation, however, these outputs are often different. Averaged together, the random components of these variations are minimized, producing a more robust output for subsequent signal processing.

The mean or average current can be computed in analog VLSI hardware by using the simple, four transistor circuit shown in Figure 4.1. This circuit uses currents generated by MOSFETs as its inputs; the MOSFET gate voltages are the output voltages of a cluster of sensors operating under the same conditions (temperature, doping, etc....). The output current or voltage of the circuit reflects the mean or mathematical average of its input currents. To understand this circuit, we can apply Kirchoff's current law to the common node (V_{mean}) in this circuit as follows:

$$\begin{aligned} \sum_n I_n &= \sum_n I_{\text{mean}} = N I_{\text{mean}} \\ I_{\text{mean}} &= \frac{1}{N}\left(\sum_n I_n\right) = \text{Mean Current} \end{aligned} \tag{4.2}$$

Since the node V_{mean} is connected to the same point at every element within a cluster of sensors, the current in the transistor M_3 must be the same for all the elements in a cluster. For this reason, M_3 sinks the mean current; either the mean current, I_{mean}, or the gate voltage at M_3, V_{mean}, may be used as the aggregate input to subsequent signal processing.

Process variation and transistor mismatch in the CMOS fabrication process may affect the accuracy of the mean current computation. However, in a mature fabrication process, these variations become random [54] and are minimized in this circuit by the mean computation itself, causing their effect on circuit performance to be minimal. The mean current or voltage reflects primarily the activity of the chemical sensors that generate the input currents to the circuit rather than transistor variations within the circuit itself. Since the mean current is inherently insensitive to random fluctuations within individual sensors, the mean output current provides a more robust input signal to subsequent signal processing stages than could be provided by the output current of any individual sensor within a cluster.

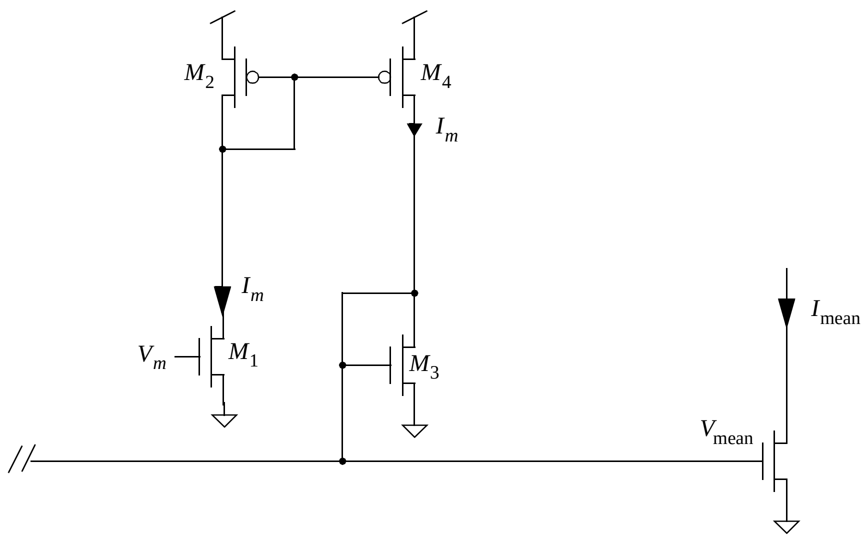

Figure 4.1: The Mean Current Circuit

The input voltage V_n is an output from a chemical sensor. Since the common node V_{mean} is attached to the same point in all array elements, the sum of all the input currents I_m must equal MI_{mean} where M is the total number of homogeneous sensor elements in a cluster. The current I_{mean} is the mean current of all the inputs I_m which correspond to a cluster of sensor outputs operating under the same set of conditions. For the testing performed in this research, a homogeneous cluster of sensor outputs have a common operating temperature T.

4.1.2 Mean Detection with Outlier Elimination

In such sensors as ChemFETS, broken sensors generate outputs that are vastly different from the outputs of healthy sensors [19]. To eliminate the effect of broken sensors in subsequent computations, it is necessary to nullify these signals during homogeneous processing. The outlying outputs generated by broken sensors are no longer representative of activity in the chemical sensing environment and therefore, should be entirely eliminated from the computation of the mean output current for a cluster. In the case where the sensor failure mode produces an abnormally low output, the mean calculation can be modified as follows to eliminate the effect of the broken sensors:

$$f_T(i_m) = \frac{1}{M}\left(\sum_k i_k\right) \text{for all } i_k > (1-\alpha)\ f_T(i_m) \tag{4.3}$$

Similarly, when the failure mode results in an abnormally high output, the mean calculation is as follows:

$$f_T(i_m) = \frac{1}{M}\left(\sum_k i_k\right) \text{for all } i_k < (1+\alpha)\ f_T(i_m) \tag{4.4}$$

where the ratio α defines the outlier limit in both (4.3) and (4.4). Circuits designed to implement (4.3) and (4.4) are shown in Figure 4.2 and Figure 4.3 respectively. An understanding of how these circuits calculate $f_T(i_m)$ or I_{mean} may be obtained through the following analysis. The voltage V_{preset} resets the circuit in order to calculate the unmodified mean current based on all the sensory inputs. While V_{preset} is active, the circuit uses all of the inputs I_m to calculate the true mean current, I_{mean}. After V_{preset} is released, however, any outliers lying outside a certain ratio (α) below or above the mean for Figure 4.2 and Figure 4.3 respectively are eliminated from the mean calculation. Consider, for example, the elimination of outliers that lie below α of the mean in Figure 4.2. In elements where the sensor output current is not outlying, the transistor M_8 remains turned on and the circuit operates identically to the original mean current circuit of Figure

4.1. Since the transistor M_8 remains on for these elements, the total current contributed to the common node, V_{mean} for this particular element is:

$$I_{M_4} - I_{M_3} = I_m - I_{mean} \tag{4.5}$$

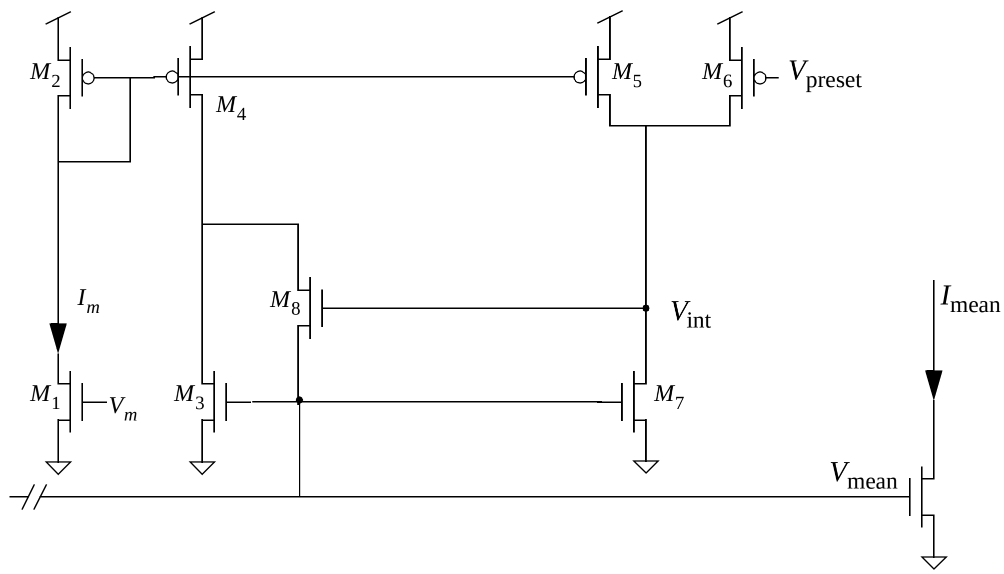

Figure 4.2: The Mean Current Circuit with elimination of Low Outliers

If the input current I_m to a particular circuit element is less than a certain percentage α of the mean current I_{mean}, the voltage V_{int} goes low, turning the NFET M_8 off. When M_8 is off, the mth input current I_m is eliminated from the calculation of the mean current by disconnecting the contribution of the current I_m to the common node V_{mean}. Therefore, for an outlying current I_m, the mth element does not affect the voltage at the common node, V_{mean}. The outlier percentage α is set by the aspect ratio of M_4 relative to M_5. V_{preset}, when low, allows the circuit to be reset in order to calculate the mean current without outlier removal, ensuring a reproducible initial condition for the circuit.

If the input current, I_n, lies below a certain ratio α of the mean, the transistor M_8 turns off, disconnecting the mth element from the common node. For these outlying elements, the input current, I_m, does not affect the common node voltage, V_{mean}. If a current, I_m, drops below α times the mean, it is no longer included in the calculation of the mean current I_{mean}. When an outlying current I_m is removed from the calculation of the mean, the mean current increases sharply. An outlying I_m must then surpass the new higher outlying current limit to be included in the mean calculation again. The inherent hysteresis in this circuit prevents oscillation and instability around the switching point set by the outlier limit α. The preset transistor also prevents the hysteresis in these circuits from allowing an improper calculation of the mean. Since the definition of the absolute outlier limits is based on the inputs currently used to calculate the mean, it may be necessary to periodically recalculate the mean based on all of the inputs in order to ensure proper selection of outliers.

The outlier limit α can be set by adjusting the aspect ratio of M_4 relative to M_5 and keeping the aspect ratios of M_4 and all other transistors equal. The resulting outlier limit α is then as follows:

$$\alpha = \frac{(W/L)_4}{(W/L)_5} \tag{4.6}$$

Elimination of high outliers can be done in a similar manner and is shown in Figure 4.3. For inputs I_m that lie a certain ratio α above the mean, the transistor M_8 turns off, resulting in no contribution to the common node, V_{mean} from the outlying element. As in the low outlier removal circuit, the contribution to the common node corresponding to non-outlying elements:

$$I_{M_4} - I_{M_3} = I_m - I_{\text{mean}} \tag{4.7}$$

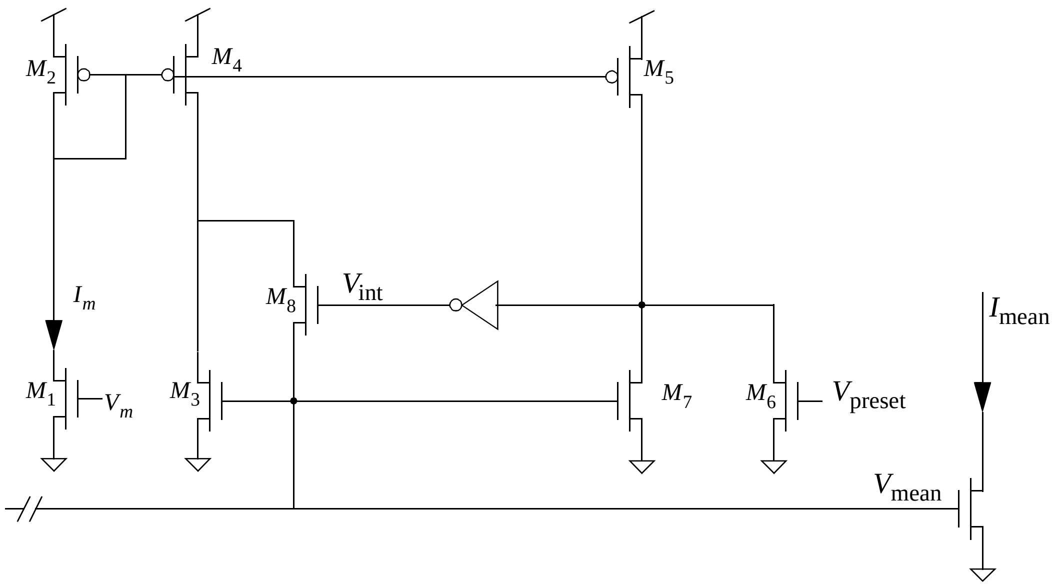

Figure 4.3: The Mean Current Circuit with elimination of High Outliers

If the input current I_m is greater than a certain percentage α of the mean current I_{mean}, the voltage V_{int} goes low, turning the NFET M_8 off. When M_8 is off, the nth input current I_m is eliminated from the calculation of the mean current by disconnecting the contribution of the current I_m to the value of the common node voltage V_{mean}. The outlier percentage α is set by the aspect ratio of M_3 relative to M_7.

Similar to the previous low-outlier removal circuit, the outlier limit α is set by adjusting the aspect ratio of M_7 relative to M_3 and keeping the aspect ratios of M_2, M_4, and M_5 equal. The resulting outlier limit α is then as follows:

$$\alpha = \frac{(W/L)_7}{(W/L)_3} - 1 \tag{4.8}$$

If it is desired to eliminate both high and low outliers, the two circuits of Figure 4.2 and Figure 4.3 may be combined into the circuit of Figure 4.4. For these elements, if the input current I_n lies below $\alpha_1 I_{mean}$ or above $\alpha_2 I_{mean}$, it is not included in the computation of the mean current because the transistor M_8 or M_9 is turned off for the *m*th processing element. If it is desired to have control of the outlier limit during actual system operation (on-line), the outlier removal limit may be established in a more flexible manner, such as through the control of source voltages in the comparator stage of these circuits. Aspect ratio control is used here for its accuracy in setting the outlier removal limit α.

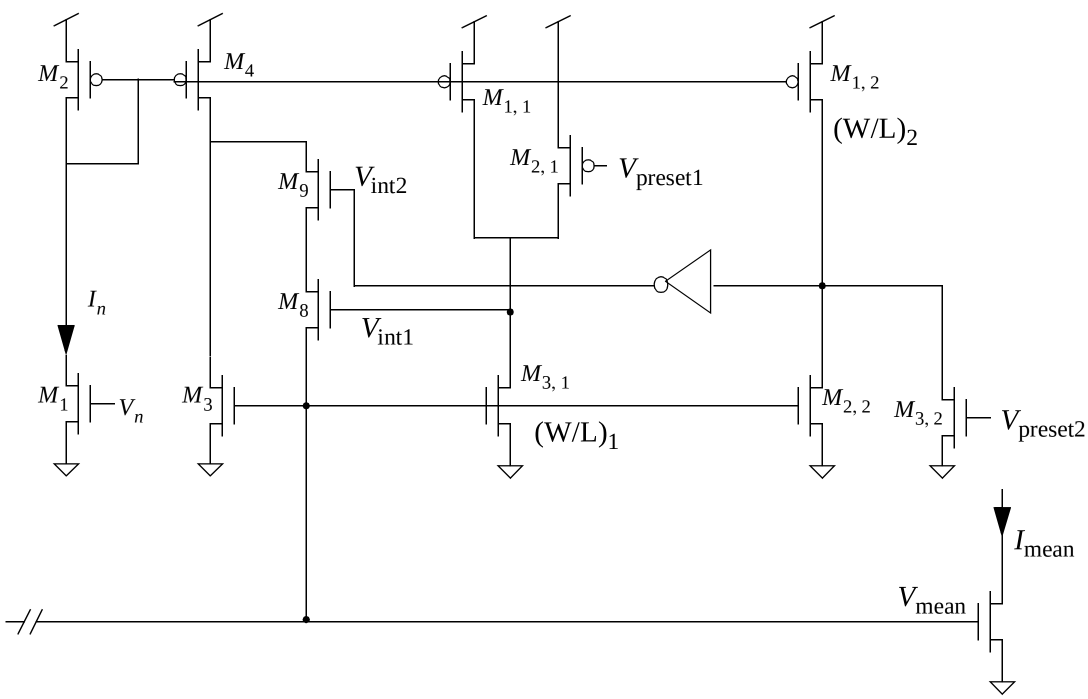

Figure 4.4: The Mean Current Circuit with Elimination of High and Low Outliers

The circuit above combines the elimination of low outliers (Figure 4.2) and the elimination of high outliers (Figure 4.3). The low outlier percentage α_1 is controlled by the circuit components above marked with a subscript of 1. The high outlier percentage α_2 is controlled by the circuit components above marked with a subscript of 2. Note that the high and low outlier limits, α_1 and α_2, can be controlled independently through the aspect ratios $(W/L)_1$ and $(W/L)_2$.

4.2 Circuit Characterization: Experimental Results

Four circuits designed to preprocess an array of analog sensory input data have been fabricated in a standard analog 2.0µm, *n*-well CMOS process using the MOSIS fabrication service. These four circuits are as follows:

- One 16 element array for averaging sensory input with no outlier analysis
- One 10 element array for averaging sensory input with elimination of low outliers
- One 10 element array for averaging sensory input with elimination of high outliers
- One 10 element array for averaging sensor input with elimination of high and low outliers

As part of circuit testing, the electrical characteristics of each of these circuits have been translated to their corresponding effect on a complete chemical analysis system that uses such thin-film sensors as tin-oxide. Circuit mismatch, resolution, and similar parameters are treated as important only in the manner in which they affect the detection accuracy of an array of chemical sensory input to which these circuits will ultimately be connected.

The following data have been collected from each circuit and are described in detail through the remainder of this section:

- Typical circuit behavior
- Accuracy and robustness of mean calculation
- Accuracy and robustness of outlier detection and removal

4.2.1 Typical Circuit Behavior

Typical behavior of the mean-detection circuit with no outlier detection or removal (Figure 4.1) is shown in Figure 4.5. Fifteen of the inputs to this sixteen element array are held at a single current 0.85nA. The remaining input current is varied by sweeping the gate voltage of the input MOSFET in the neighborhood of the other 15 inputs while the mean output current is monitored. The switching characteristics are plotted in terms of input currents rather than voltages in order to remove the exponential dependence of the mean computation on the input voltages while the circuits are operating in the subthreshold regime. Ideally the output current is just the mathematical mean of the input currents:

$$I_{\text{expected}} = \left(\frac{1}{16}\right)\sum_{m=1}^{16} I_m = I_{\text{mean}} \tag{4.9}$$

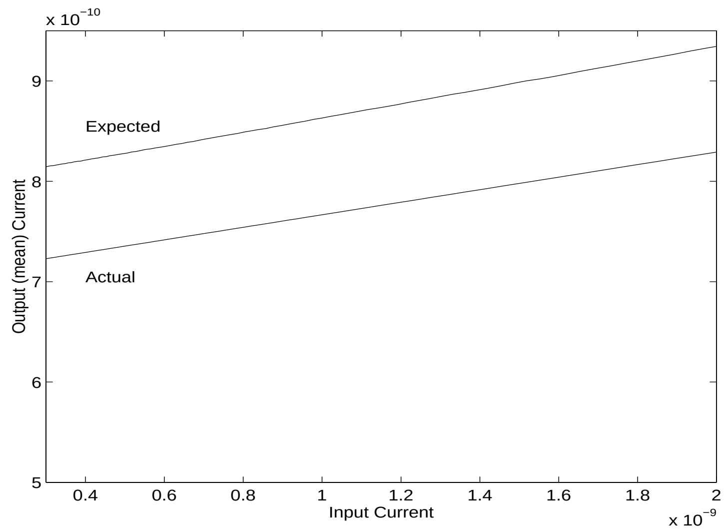

Figure 4.5: Typical Behavior of the Mean Detection Circuit with no Outlier Removal

Typical experimental switching characteristics for the mean-detection circuit with no outlier removal (Figure 4.1) are shown and compared to the expected behavior of this circuit. The upper curve is the expected behavior and the lower curve is plotted from experimental data. The input voltages and the mean output voltage are proportional to the natural log of the currents shown here. When applied to actual chemical sensing systems, process variations and mismatch in this circuit can cause the final output voltage of these circuit elements to represent some concentration that deviates from the actual concentration of gas in the sensing environment. As long as these deviations are small compared to those found in individual sensors, the mean detection circuit is able to improve the overall robustness of the sensing system.

Deviations from the expected transfer behavior (upper curve) and the actual transfer behavior (lower curve) in Figure 4.5 are assumed to be largely due to process variations and fabrication mismatch in the circuits themselves and create a concentration error in the chemical sensing systems in which these circuits are used. Circuit offset should be an insignificant (less than 10%) percentage of the sensor error in order for these circuits to be a useful addition to the chemical sensing system as a whole. Circuit error are discussed in further detail in Section 4.2.2

Typical behavior of the mean calculation circuit with low outlier removal is shown in Figure 4.6. Similar to the simple mean-detection circuit discussed above, all but one of the inputs in this circuit are held at 0.6 V or 3.87nA; differences between currents generated by the same gate voltages in the mean current circuit and the mean current circuits with outlier removal are caused by different transistor sizing in these circuits. The remaining or tenth input, I_{10}, is swept in the neighborhood of the other inputs, and the resulting output voltage and current are monitored. Experimental results are again presented in terms of currents for clarity. While the variable input is above 50% (α) of the mean output current, the expected output current is similar to that of the mean detection circuit with no outlier removal:

$$I_{\text{expected}} = \left(\frac{1}{10}\right) \sum_{m=1}^{10} I_m = I_{\text{mean}} \tag{4.10}$$

As the variable input moves below 50% (α) of the mean output current, it is determined to be an outlier and is removed from the mean current calculation. The expected output current is then:

$$I_{\text{expected}} = \left(\frac{1}{9}\right) \sum_{m=1}^{9} I_m = I_{\text{mean}} \tag{4.11}$$

The variable input I_{10} is no longer included in the mean calculation, resulting in a sharp increase in the mean current I_{mean}. Results for aspect ratio control of the low outlier limit are shown in Figure 4.6, where the outlier limit α has been set at 0.5 (50% outlier removal limit).

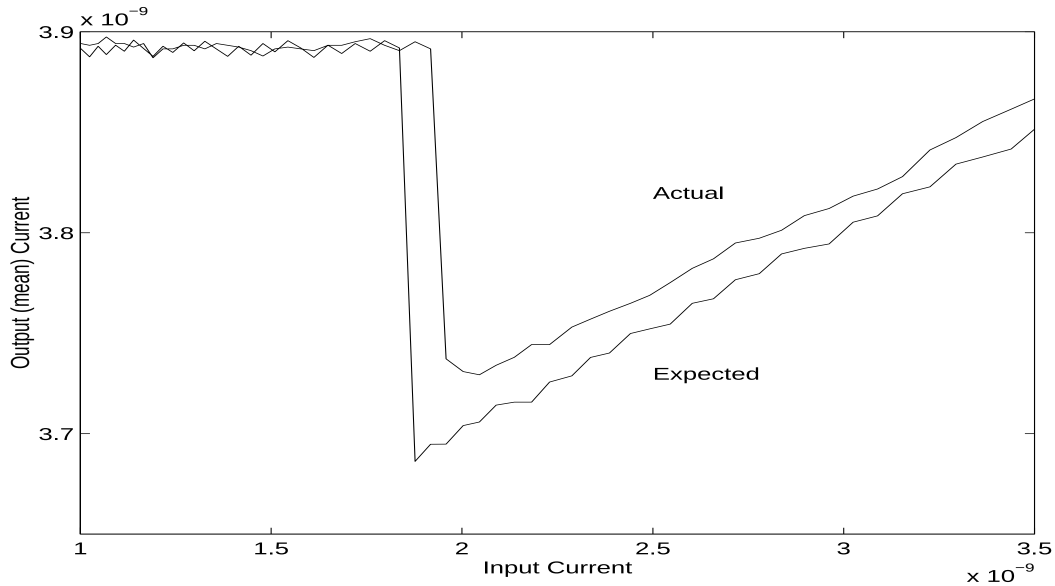

Figure 4.6: Typical Behavior of the Mean Detection Circuit with Low Outlier Removal

Typical experimental behavior for the mean-detection circuit with low outlier removal (Figure 4.2) are shown and compared to the expected behavior of this circuit. The lower curve is the expected behavior of these circuits while the upper curve represents actual behavior; the expected output current is just the mathematical mean of the non-outlying input currents. The outlier threshold α is set at 0.5 for these tests. A large part of the deviations between expected and actual behavior of these circuits is a result of process variation and mismatch and is discussed further in Section 4.2.2.

Figure 4.7 illustrates typical behavior for the mean-detection circuit with high outlier removal. As in the previous outlier elimination circuit, the high outlier limit is controlled by changing aspect ratios in the comparator stage relative to aspect ratios in the mean detection circuit itself.

For this particular circuit, the high outlier limit α has been set such that any input over twice the average current is eliminated from the calculation of the mean current. As in previous circuits, all but one of the inputs is held at a particular current (4.3nA) while the remaining input is swept in the neighborhood of the other inputs. The mean current shifts with the swept input, until the input surpasses the outlier limit *w*. As the swept input exceeds the outlier limit, it is removed from the mean calculation, resulting in a sharp decrease in the mean output; after this sharp decrease, the mean output remains fairly constant because further changes in the swept input no longer affect the calculation of the mean.

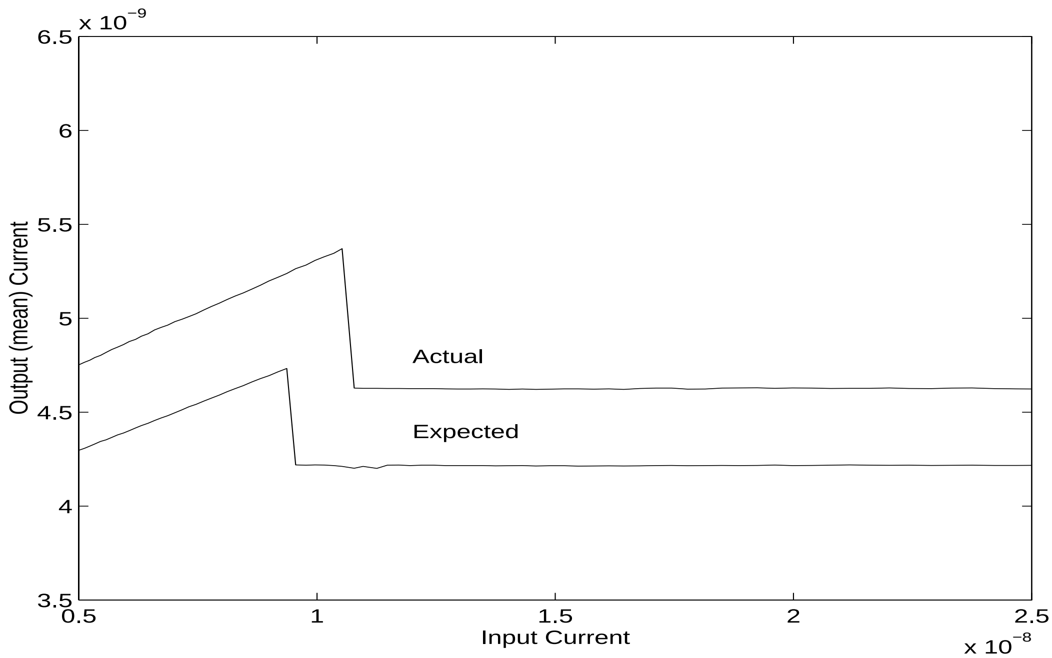

Figure 4.7: Typical Behavior of the Mean Detection Circuit with High Outlier Removal

Typical experimental characteristics for the mean-detection circuit with high outlier removal (Figure 4.3) are shown and compared to the expected behavior of this circuit. The upper curve is the expected behavior while the lower curve represents expected behavior of the circuit. The outlier threshold α is set at 1 for these tests, so that outlier removal occurs when an input current surpasses twice the mean current. Again, deviations between expected and actual behavior are a direct result of process variation and mismatch in the component transistors.

Finally, Figure 4.8 illustrates the behavior of the dual-outlier removal circuit where outliers below 50% of the mean current and above 200% of the mean current are eliminated from the mean calculation. The typical behavior shown in Figure 4.8 is obtained in a similar manner to the results for the single outlier circuits.

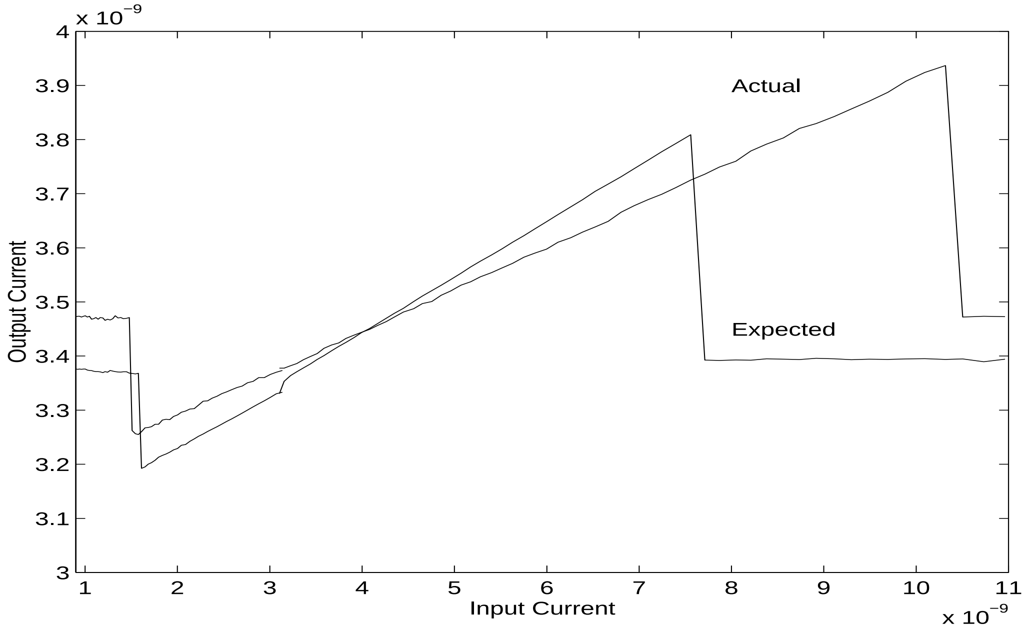

Figure 4.8: Typical Behavior of the Mean Detection Circuit with Dual Outlier Removal

Typical experimental characteristics for the mean-detection circuit with dual outlier removal (Figure 4.4) are shown and compared to the expected behavior of this circuit. The upper curve is the expected behavior while the lower curve represents expected behavior of the circuit. The outlier threshold α is set at 0.5 for the low-outlier limit and at 1 for the high outlier limit. Input currents are removed form the mean calculation when they fall below 50% of the mean current or above 200% of the mean current.

Using the voltage V_{preset} in all three outlier removal circuits, it is possible to switch between mean calculations with no outlier removal to another computation that does remove outliers outside the limit α discussed previously. The voltage V_{preset} ensures that before outliers are removed, a true mean is calculated that includes all inputs. When V_{preset} is released, outliers are then determined and removed based on this original mean calculated when V_{preset} is active. Figure 4.9 shows typical switching behavior for the elimination of low outliers when V_{preset} is active and after it has been released. The point of deviation between the two curves corresponds to the location of the outlier limit α.

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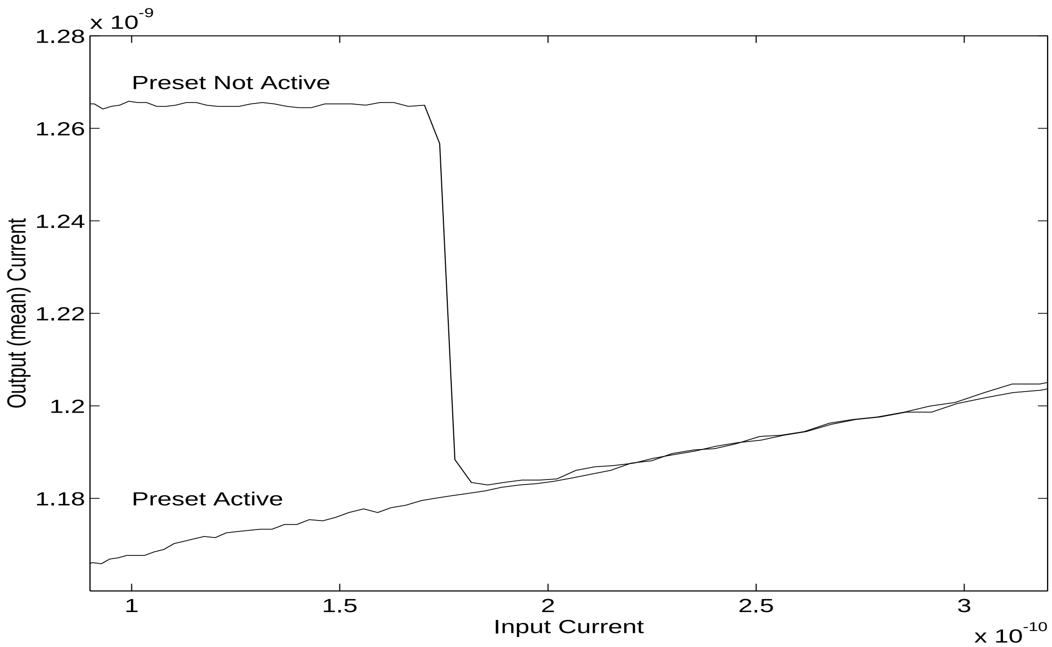

Figure 4.9: The effect of Preset Activity on the Outlier Removal Circuits

Shown above is switching behavior for the low outlier removal circuit when V_{preset} is active and after it has been released. When V_{preset} is active, the mean is calculated considering all of the inputs regardless of their location. After V_{preset} is released, the outliers are detected and removed from the outlier detection. V_{preset} ensures reproducibility of the final mean output when outliers are present.

Deviations between the actual and theoretical switching behavior of these circuits can be separated into a number of components. When connected to an array of chemical sensors, these deviations can cause corresponding errors in concentration information. For example, the relationship between concentration, sensor output voltage, and resulting input current to the averaging circuit for an output range of 1V and a load resistance of $10k\Omega$ ohms are shown in Figure 4.10 for the TGS822, tin-oxide chemical sensor (Figaro Engineering [51]). Other solid-state sensors, tin-oxide and otherwise, demonstrate similar transduction relationships for various reducing chemicals. Using these transduction relationships, circuit errors can be approximately converted to apparent errors in the sensory output data in order to compare the error contributions of sensor and circuit to the overall system error

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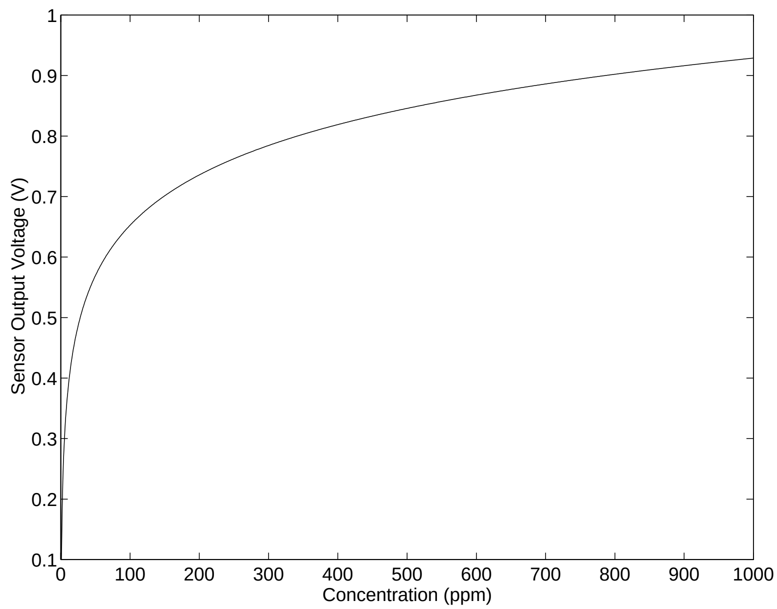


Figure 4.10: Typical Transduction Relationships for Solid-State Chemical Sensors

Shown above are typical relationships between sensor output voltages and chemical concentration for a typical reducing chemical in a TGS822, tin-oxide sensor. The sensor power supply is 1V and the load resistance is $10\mathrm{k}\Omega$. Relationships for other conductivity-based sensors are similar.

4.2.2 Accuracy of Mean Calculation

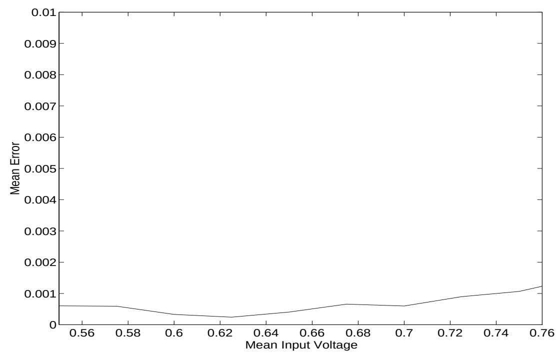
Since they affect the performance of the overall sensing system to which they will be connected, deviations between actual and expected behavior in the calculation of the mean current are evaluated in this section over a range of input currents and voltages. Similar variations between actual and expected behavior in the location of the outlier limit α are discussed in the following section. Deviations from expected behavior affect the performance of a complete chemical sensing system as a form of concentration error. Concentration offset is defined as the difference between the actual concentration of a chemical in the sensing environment and the expected concentration suggested by the output of a homogeneous cluster of preprocessed sensor outputs. This offset not only causes an error in the detected concentration but can also affect the discrimination capability of the system. If this error is sufficient to change the features of a particular chemical signature extracted by signal processing of a heterogeneous array of sensors, it decreases the robustness of the system. To evaluate the impact of circuit offset in these systems, we assume that if the circuit contribution to the overall offset is small (less than 10% of the variation in individual sensor performance), then it does not have a significant impact on the concentration detection or discrimination capability of the overall chemical sensing system. Offsets are shown for the mean detection circuits in Figure 4.11 for a typical sensor operating range (0.55-0.75V for a sensor power supply voltage of 1V). For all the mean detection circuits, the mean error remains below 5mV which is substantially less than 10% of the 0.1V error [56] found in a typical tin-oxide chemical sensor in this operating range.

The offset (difference between expected and actual outputs) for these circuits are tabulated in Table 5.1 and compared to the error found in individual sensors (circuit impact). The impact of the offset of the mean detection circuits on the overall system performance is called circuit impact and is calculated as the ratio of circuit offset to the sum of circuit and sensor offset. The arrays that use outlier removal techniques exhibit more error because of leakage through the control transistor in the diode-connected transistor, M_8, of each element and because of the fact that the 10-element arrays average out less fabrication mismatch than the 16-element mean detection circuit.

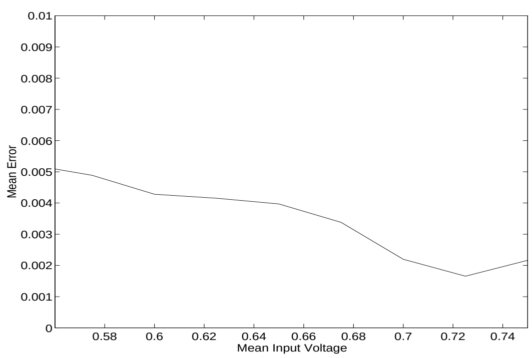
In integrated sensing systems, where the chemical sensors in an array are more closely matched, these errors can became a much larger percentage of total error. However, circuit offset can also be improved through by using better layout techniques such as common centroid layout and by using larger transistor areas to minimize the impact of fabrication mismatch.

TABLE 4.1: Maximum Offset Generated by the Mean-Detection Circuits

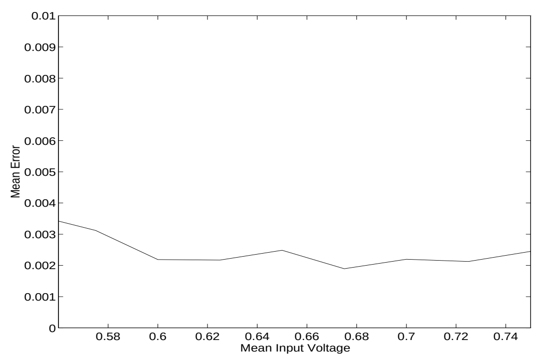
Circuit	**Circuit Voltage Offset**	**Typical Sensor Offset**	**Circuit Impact**
Mean Detection (No Outlier Removal)	0.001V	0.1 V	1.0%
Mean Detection (Low Outlier Removal)	0.005V	0.1V	5.0%
Mean Detection (High Outlier Removal)	0.003V	0.1V	3.0%



(a) No Outlier Removal



(b) Low Outlier Removal



(c) High Outlier Removal

Figure 4.11: Offset in the Mean Detection Circuits

Shown above are the differences between actual and expected behavior for the mean detection circuits with: (a) no outlier removal, (b) low outlier removal and (c) high outlier removal. In each case, all but one of inputs are held at a particular voltage and the remaining input held at another voltage. The predominant input voltage is shown on the x-axis above and the resulting output offsets on the y-axis. Since these circuits operate in subthreshold, the voltage offset shown above is logarithmically related to the corresponding offset in current.

4.2.3 Resolution in the Mean Detection Circuits

In addition to understanding what types of offsets (differences between expected and actual behavior) the mean detection circuits generate in actual chemical sensing systems, it is also important to understand the impact that these circuits have on the system resolution. Resolution is defined as the maximum accuracy to which a particular concentration can be determined, and is a function of how the outputs of identical sensors vary in actual operation. A system with 5% resolution can detect concentrations within 5% of their actual value. The resolution of the mean detection circuits and the chemical sensors themselves is also important for evaluating the discrimination capability of the system, because it establishes the robustness and reproducibility of the relationship between two sensory array outputs.

Circuit resolution can be measured by rearranging the inputs to each of the mean-detection circuits. If we hold all but one of the inputs at a particular value and the remaining input at another value, the resolution of the system is the maximum variation in the output voltage when the last input is switched from element to element in the array. Depending on the mismatch among the circuit elements, the aggregate output of the system will vary as the location of certain inputs changes. The mismatch among circuit elements, as measured in this fluctuation in circuit output, affects the overall concentration resolution of the sensing system. Like the offset generated by the mean detection circuits evaluated in the previous section, it is assumed that if the resolution of these circuits is substantially better (at least an order of magnitude) than the resolution of an individual sensor, the circuits themselves are sufficiently robust to be used in complete chemical sensing systems. Resolution for the mean detection circuits is shown in Figure 4.12.

Resolution for these circuits are comparable due to the similarities in the mean-detection portion of each circuit and in the layout of this portion of the circuit. The only difference between the simple mean detection circuit (with no outlier removal) and the circuits with outlier removal is the presence of the outlier control transistors M_8 which is always fully turned off or fully turned on, thereby minimizing the effect of fabrication variations in this transistors on the circuit resolution.

The minimum resolution for each circuit is tabulated in Table 5.2 and compared to the corresponding concentration resolution for a typical chemical sensor. The circuit impact is calculated as the ratio of circuit resolution to total resolution as follows:

$$\text{Circuit Impact} = \frac{R_{\text{circuit}}}{R_{\text{sensor}} + R_{\text{circuit}}} \tag{4.12}$$

The resolution of these circuits is approximately 30 times better than that of an individual sensor and does not have substantial impact on the predicted performance of the overall chemical sensing system.

TABLE 4.2: Resolution of the Mean Detection Circuits

Circuit	Circuit Resolution	Sensor Resolution	Circuit Impact
Mean Detection (No Outlier Removal)	0.0031 V	0.10 V	3.1%
Low Outlier Removal (Aspect Ratio Control)	0.003 V	0.10 V	3.0%
High Outlier Removal (Aspect Ratio Control)	0.0021 V	0.10 V	2.1%

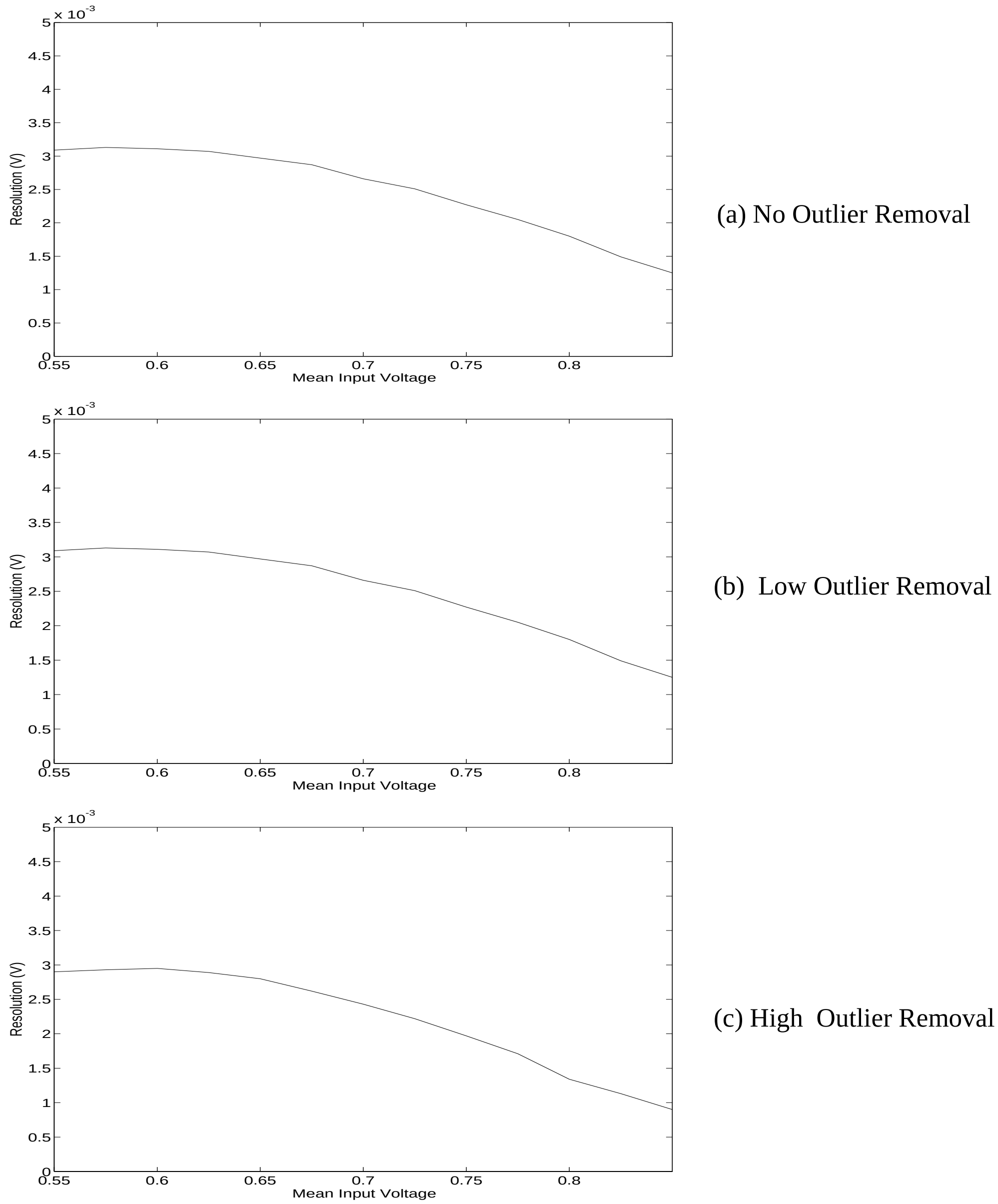


Figure 4.12: Resolution in the Mean Detection Circuits

Shown above are resolution across a range of mean inputs for the mean detection circuits: (a) with no outlier removal (b) with low outlier removal) and (c) with high outlier removal. All results above are shown with all circuit elements active, where no actual outliers are present. To determine the resolution, all but one of the inputs in each array is held at a particular voltage; the remaining input is held at another voltage different from the other nine inputs; the mean output voltage is then monitored as this lone input is switched from element to element. The maximum difference in mean output voltage across the array is the resolution plotted above. In terms of chemical sensing systems, resolution represents the finest concentration difference that can be detected for a particular chemical.

4.2.4 Accuracy of Outlier Removal

The accuracy with which the outlier removal limit α is determined in the mean-detection circuits is also relevant to overall chemical sensing system performance. In this section, we evaluate the two primary components of the outlier removal process:

- Switching point: the outlier ratio α at which the outlying input is completely removed from the mean calculation.
- Switching range: the input voltage range across which the outlying input contributes only partly to the calculation of the mean. The switching range is directly related to the gain with which an input goes from being non-outlying to outlying.

The switching range is tabulated in Table 5.3 and in all circuits, is a small percentage of the common mode or mean input voltage.

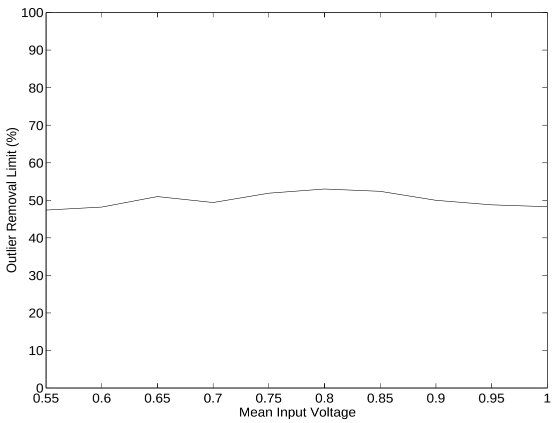
TABLE 4.3: Switching Range for Outlier Removal Circuits

Circuit	Switching Range
Low Outlier Removal	.0006V
High Outlier Removal	.0008V
Dual Outlier Removal	.001V

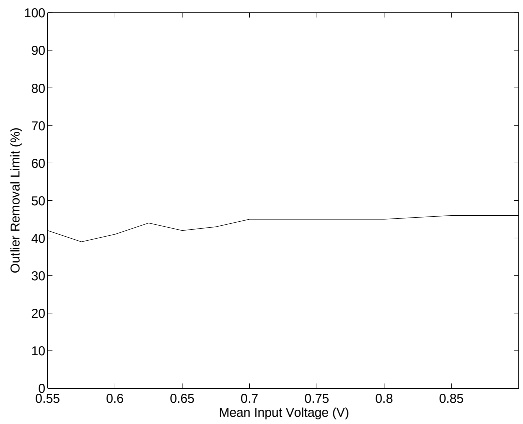
The outlier limit α (switching point) has been monitored as a function of mean input voltage and is shown in Figure 4.13. Variations between these experimental outlier limits and the expected outlier limit for these circuits can be attributed directly to fabrication mismatch in the aspect ratios of the fabricated transistors. This mismatch is different for the dual outlier removal circuit than for the single outlier removal circuits, because these two groups of circuits were fabricated on different runs. The effects of mismatch could be further minimized by increasing transistor area in the key (ratioed) transistors for each circuit.

Single Outlier Removal

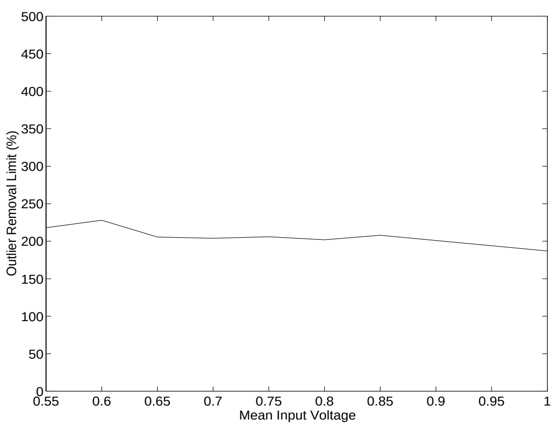
Dual Outlier Removal



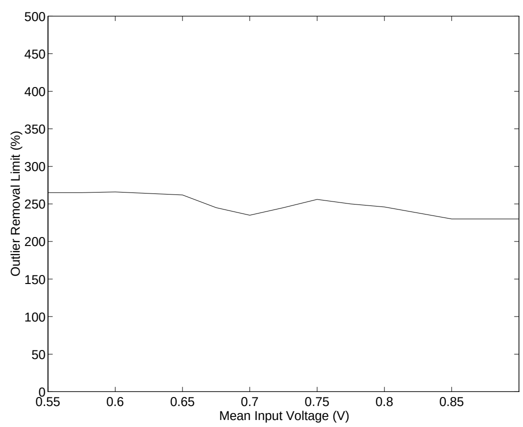
(a) Low Outlier Removal Circuit



(b) Low Outlier Removal Half of Circuit



(c) High Outlier Removal Circuit



(d) High Outlier Removal Half of Circuit

Figure 4.13: Variations in the Outlier Removal Limit

Shown above are variations in the outlier removal limit α for the (a) low outlier removal circuit, (b) high outlier removal circuit and (c,d) dual outlier removal circuit. Variations between the expected (expected) limit and the actual limits shown here can be largely attributed to fabrication mismatch. Ideally, low outliers should be removed when they fall below 50% of the mean value and high outliers when they exceed 200% of the mean value.

4.3 System Testing

In order to demonstrate the viability of the mean detection circuits for use in real chemical sensing systems, the four circuits discussed in this chapter have been tested on arrays of discrete, tin-oxide chemical sensors. The stability of the averaged outputs has been sufficient to demonstrate its viability for homogeneous array processing in chemical sensing systems.

4.3.1 Experimental Setup

Arrays of eight and ten tin-oxide sensors have been used to test the averaging circuits and outlier removal circuits respectively using the set-up shown in Figure 4.14a. Each tin-oxide sensor (Figaro TGS822) contains its own on-board heater; these heaters are controlled independently by a voltage divider and a buffer. For this experiment, all of the heaters are maintained at 4.85 V, which according to manufacturer's specifications, corresponds to a temperature of approximately 350°C. Because the temperature of each sensor is independently controlled, each sensor output is sensitive not only to variations in the actual sensor surface but also to variations in the heaters themselves. The outputs of each sensor array are connected to the inputs of the appropriate averaging circuits and the circuit outputs monitored by several source-measurement units via an IEEE-488 interface and Unix-based workstation. All of the sensors are allowed to stabilize for a week at the desired operating temperature before testing is performed. A chemical (liquid ethanol) is introduced into a large chamber (Figure 4.14b) and allowed to evaporate into the chamber. A valve between this chamber and a smaller testing chamber is then opened allowing the gas to diffuse into the environment of the sensor arrays. A fan inside the testing chamber keeps the gas well mixed and evenly distributed. A large amount of the gas is first introduced into the chamber, allowing the sensors to approach saturation and the averaging circuits to be tested in saturation mode. Then, the testing chamber is vented slightly, to force the sensor array out of saturation and the tests on the averaging circuits are repeated. The sensor outputs are monitored for approximately 30 minutes in both saturation and non-saturation mode. Because of small leaks in the testing chamber, the concentration of gas and subsequently, the sensor outputs, do decrease slightly during this period. However, because a decrease in concentration has a systematic rather than random effect on sensor performance, the averaging circuit outputs will reflect this decrease rather than eliminate it, as would be expected for any concentration change in a homogeneous array.

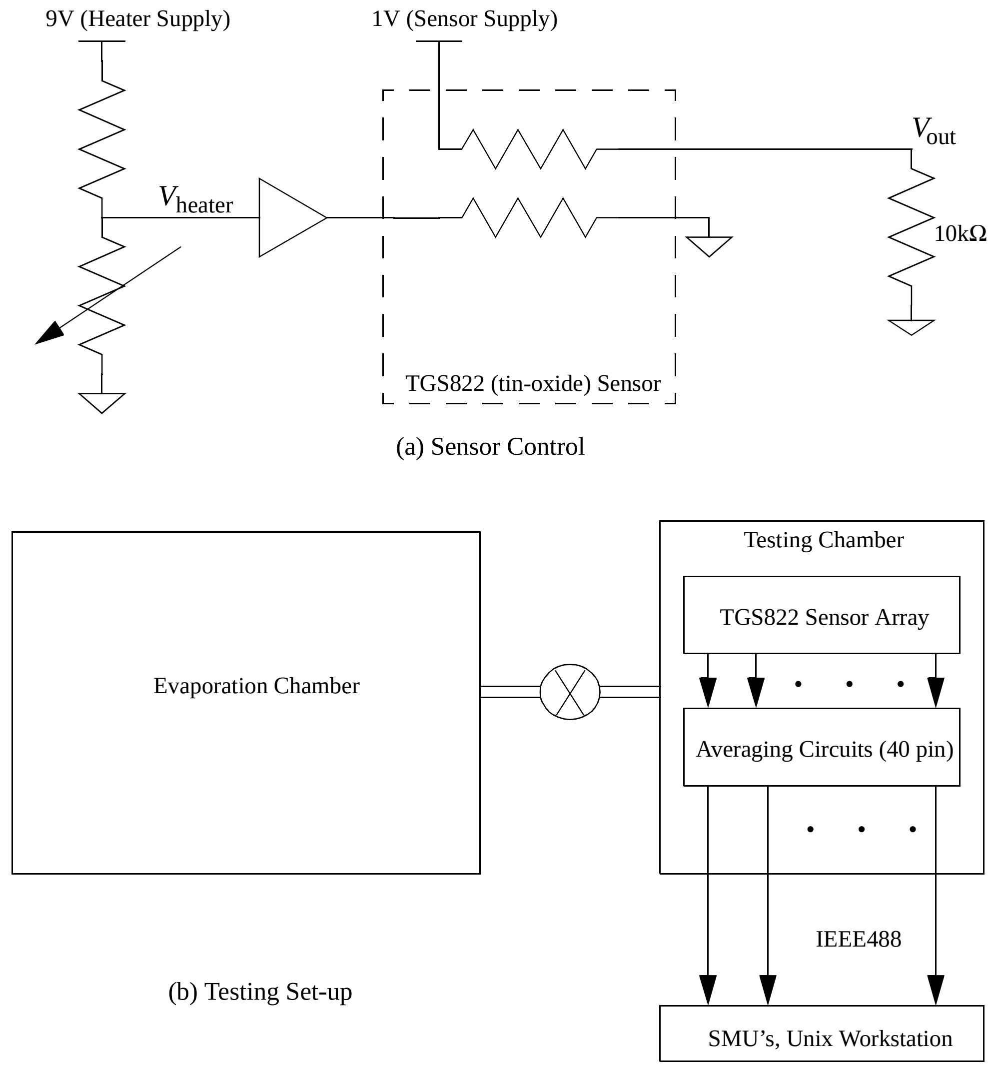


Figure 4.14: Experimental Set-up for Testing the Averaging Circuits

Shown above is the testing set-up for evaluating the performance of the averaging circuits on an array of tin-oxide sensors. Each sensor (a) consists of a resistive heater and a chemically sensitive resistor; the heater voltage is maintained at 4.86V or approximately 350°C for each sensor. The sensor output voltage is then taken across a 10kΩ load resistor. A chemical (ethanol) is introduced into the (b) evaporation chamber and allowed to evaporate and diffuse throughout the chamber. A valve between the two chambers is opened, allowing the evaporated gas to move into the testing chamber where it is sensed and averaged. The outputs are monitored by various source-measurement units and a Unix-based workstation via an IEEE-488 interface.

4.3.2 Experimental Results

Two types of tests were performed using the experimental set-up described above. The first test (Figure 4.15) evaluates the response of the tin-oxide sensor array when the sensor responses are not saturated in the mid-range of operation. The second test evaluates the response of the array (Figure 4.16) when the sensor array is close to saturation (maximum response level).

The individual sensor responses are more variable during a non-saturated response, because they are more sensitive to the environment in this sate. In the saturated response state, however, the sensors are close to their maximum output values, where fluctuations occur only as a result of a relatively large concentration changes. During the non-saturated response, the output of the mean detection circuits generate a much smoother, less noisy output than any of the individual component sensors as the effect of random fluctuations in sensor surface reactions are eliminated; in the non-saturated response state, outliers tend to occur at the lower values where some blockage on the surface states has occurred that prevents the sensors from reacting to low chemical concentrations. During the saturated response state, the outputs of the mean detection circuits continue to remove outlying elements; in this state, however, it is removal of the high outliers that is more important, since the high outliers represent almost fully saturated sensors that are incapable of responding to further increases in chemical concentration. The broad range of sensor outputs in this experiment is due primarily to the fact that the discrete sensors used for testing come from different manufacturing batches. It is expected that, as it becomes possible to integrate these sensors onto a single substrate during the same manufacturing batch, these fluctuations will begin to decrease.

The four homogeneous processing techniques we have designed and fabricated have proven useful both at the circuit and system level for minimizing the effects of random mismatch, process variations, and environmental changes on the aggregate output for a homogeneous cluster of sensors. After the outputs of homogeneous clusters of sensors have been generated by using the techniques described in this chapter, the cluster outputs are ready for further signal processing. Subsequent signal processing uses these cluster outputs as inputs to a heterogeneous array to generate output patterns that perform chemical discrimination tasks while remaining insensitive to the more systematic errors caused of drift, concentration changes, and similar effects.

(a) Individual Sensor Outputs

(b) Processing with Low Outlier Removal

(c) Processing with High Outlier Removal

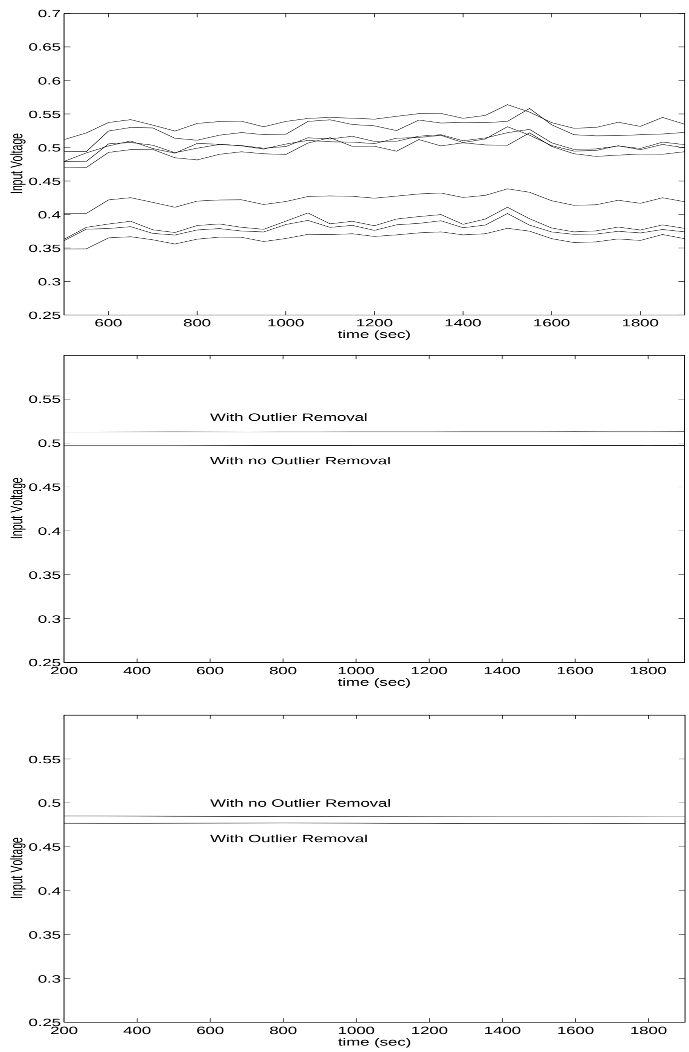
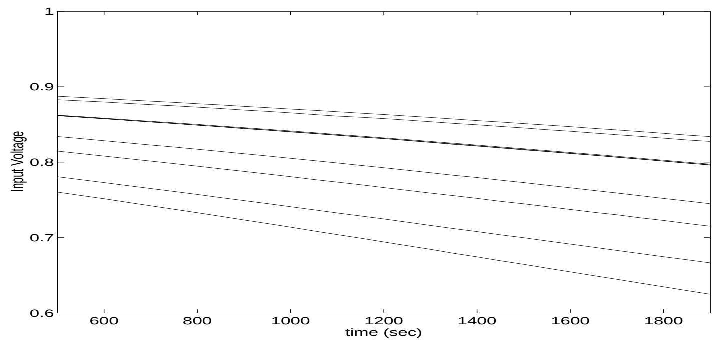


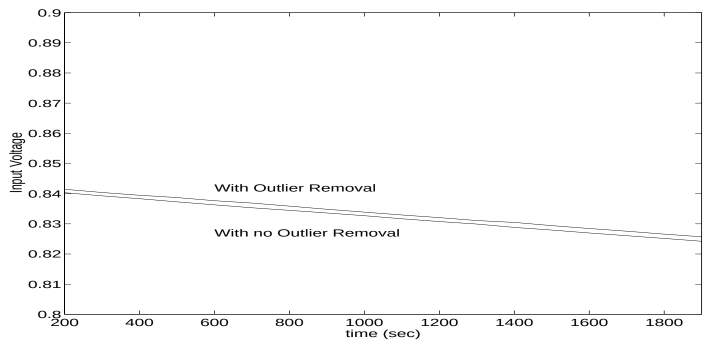
Figure 4.15: Processing of Homogeneous Clusters during a Non-saturated Response

Shown above are the responses of individual tin-oxide sensors and the response of a homogeneous array of 10 tin-oxide sensors operating at a single temperature with a small concentration of chemical present. (a) Individual sensor outputs tend to be noisy and subject to a great deal of variation. Averaging with (b) low and (c) high outlier removal produces a much smoother, less noisy output for subsequent signal processing centers. The signals shown in (a) that are less than 0.4V, though not completely broken, exhibit poor response characteristics that are not indicative of the actual chemical concentration in the sensing environment. For this reason, the low signals, in this example, should be considered outliers and removed from the mean computation.

(a) Individual Sensor Outputs



(b) Processing with Low
Outlier Removal



(c) Processing with High
Outlier Removal

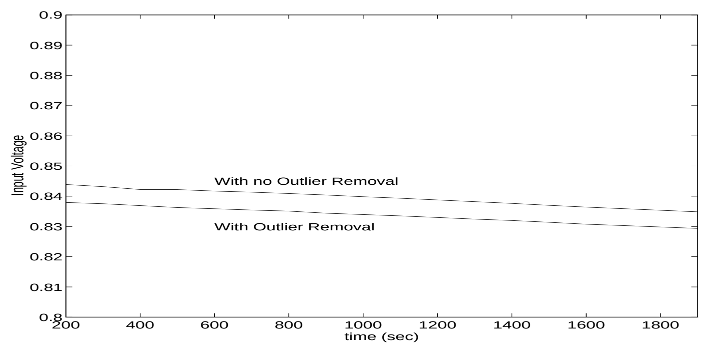


Figure 4.16: Processing of Homogeneous Clusters during a Saturated Response

Shown above are the responses of individual tin-oxides sensors and the aggregate response of a homogeneous array of 10 tin-oxide sensors operating at a single temperature. Averaging with (b) low and (c) high outlier removal produces a much smoother, less noisy output for subsequent signal processing centers.