Temperature-Sensor Research and Development, forever

Presentation by Gerard Meijer at the opening of Electronics ET2019, Sozopol, Bulgaria.

Abstract: *This paper shows why even for a limited number of specific devices R&D will never end. This is illustrated for R&D performed on solid-state temperature sensors during a period of more than 40 years. It is shown that sometimes, for basic problems important solutions are found, which can solve critical problems once and forever. However, new technologies generate new opportunities to design innovative products. Presently, new technologies are developed for the production of digital circuits. Yet, for innovative products, analog devices and circuits have to be used too. Additional work should be done, to investigate and characterize devices and circuits before they can be applied for analog applications. Lack of design capacity results in an ocean of opportunities for smart people interested in challenging design activities in the field of electronics, instrumentation and measurements.*

Introduction

In the end of the 17th and the beginning of the 18th century, the first reliable thermometers in the world were developed and produced by Daniel Gabriel Fahrenheit.

Fig. 1 Thermometer of Daniel Fahrenheit (1727).
Collection National Museum Boerhaave, The Netherlands.

Fahrenheit was born in 1686 in Danzig (Gdańsk) and was the inventor of the mercury thermometer (Fig. 1). He moved to The Netherlands, where he produced this and other instruments in his factory in the Hague. He died in the Hague in 1736. This illustrates that also the development of thermometers is the result of international activities. The thermometer was calibrated using three reference points:

1) The freezing temperature of a solution of brine made from equal parts of ice, water and a salt (ammonium chloride), (0 °F),
2) The melting point of ice (32 °F),
3) His best estimate of the average human body temperature, (96 °F); redefined later.

The choice of these reference points was smart, because now he had 2^5 and 2^6 degrees in the two temperature intervals between the reference points. He could easily sub define the scale by dividing

these interval by two and do this again and again in five and six steps, respectively. The accuracy and reproducibility of the thermometers was largely dependent of the quality of the glass bulb and tube. So, already in Fahrenheit's time good/smart technology was the basis for fabricating good sensors. May be that in that time, somebody supposed that these thermometers would be the favorable instrument to measure temperatures for once and forever.
However, a drawback of such thermometers concerns its vulnerability. Moreover, calibration was not easy. Therefore, the production of accurate thermometers should have been expensive. For complementary applications, soon alternative thermometers were developed, such as those for measuring very high or very lower temperatures.
Taking some big steps through history, we arrive in the era of solid-state sensors, where thermistors and integrated solid-state (silicon) sensors displaced the liquid thermometers.
We will show how the introduction of integrated sensors opened opportunities to improve accuracy, measurement speed, and to simplify calibration.

Integrated temperature sensors

In 1967, Bob Widlar presented a description of the temperature characteristics of base-emitter voltages of bipolar transistors at the ISSCC conference [1]. Later he presented a temperature-independent voltage reference [2] in which a correction voltage is added to a base-emitter voltage. The summed voltage equals the extrapolated base-emitter voltage at 0K. This voltage V_{BE0} (Fig. 2(c)) is mainly determined by the bandgap voltage of silicon and some other physical constants, which are immune to variations in doping levels and current density .The correction voltage was obtained by amplifying the difference between the base-emitter voltages of two bipolar transistors biased at different current densities, which difference is **P**roportional **T**o the **A**bsolute **T**emperature (PTAT). This PTAT voltage is amplified and added to a base-emitter voltage to get the reference voltage, which equals about 1240 mV. Usually some fine-tuning is required, by trimming. Moreover, some other corrections are required to compensate for the small nonlinearity of the base-emitter voltage. The circuit of Fig 2(a) generates both: a PTAT current and a bandgap reference voltage [3].

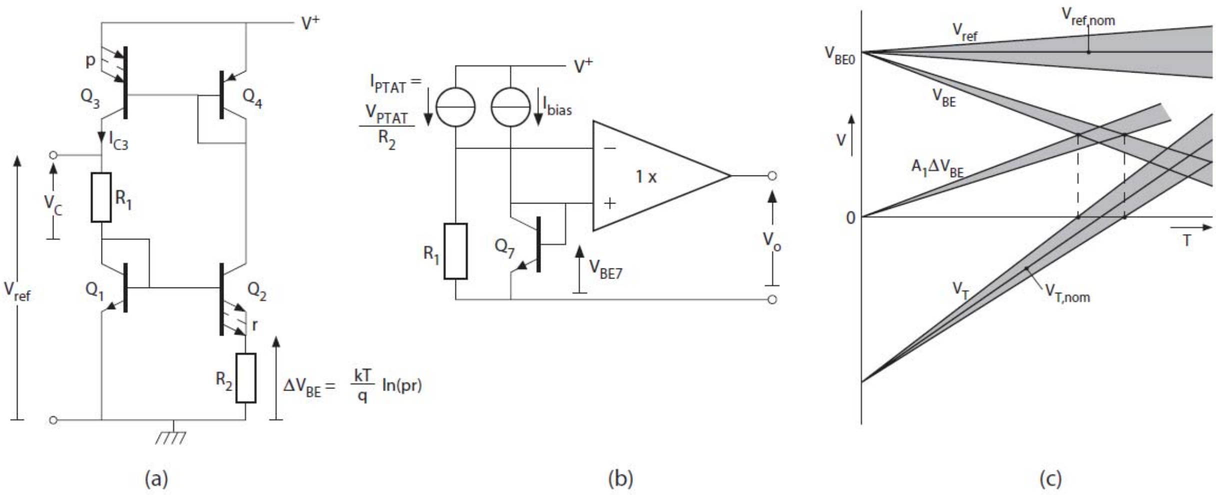

Fig. 2 Circuits to generate the basic signals in bandgap voltage references and temperature sensors [3]. (a) PTAT-current generator and bandgap-voltage generator, (b) circuit to generate a voltage with intrinsic reference and a zero at an arbitrary temperature (c) basic signals versus temperature.

In 1976, Timko [4] presented a 2-Terminal IC Temperature Sensor, which was a PTAT current source that produced a current of 1µA/K . A drawback of this popular product was that for measurements of small temperature changes around, for instance, room temperature (about 300K), the relative change of the “offset” current of 300 µA is rather small. This can be improved by subtracting a reference current from the “offset” one and amplifying the difference. However, this would require the use of a number of additional precision components. Figure 2(b) shows a better idea: Instead of subtracting a reference current or voltage, it would be a better to subtract a base-emitter voltage V_{BE}, which yields the voltage V_T (Fig. 2(c)). Because of its relatively high temperature sensitivity, this would yield a more sensitive device. As shown in Fig. 2(c), such an approach can yield two useful signals: a reference voltage V_{ref} and a highly temperature-sensitive voltage V_T. After trimming, the latter one can have its “zero” at a desired temperature. In that way a voltage at, for instance, at a Celsius or Fahrenheit scale is achieved. Moreover, Fig. 2(c) shows that the extrapolated basic signals V_{BE} and V_{PTAT} and their linear compositions V_{ref} and V_T have a well-known value at 0 K. This opens the opportunity to do calibration and trimming at a single temperature, to obtain a calibrated sensor for a wide temperature range of, for instance, -40 ^{0}C to + 130 ^{0}C. So, in contrast with Fahrenheit’s thermometers, in which three reference points were used for calibration, in integrated solid-state temperature sensors a single reference point would be sufficient! These ideas were recognized to be important and a number of people claimed to be the inventor. It was Bob Pease [5] who gave the credits to the present author, because of a publication in IEEE Journal of Solid State Circuits [6].
Note that signal processing such as adding, subtracting, multiplying, and dividing signals can easier and at lower costs be performed in a microcontroller than doing this in the hardware of the sensor. Therefore, it would be a good idea to convert the basic signals into the digital domain as soon as possible. Once the signals are in the microcontroller, also compensation for the small nonlinearity in the $V_{BE}(T)$ characteristic can easily be achieved. Yet, to make accurate integrated sensors, some on-chip processing will be necessary, such as **trimming**.
Trimming is a form of adjustment, which can make the sensors equal to each other. This adjustment is necessary, mainly because of spreading in the values of the base-emitter voltage V_{BE}. The relative spreading in V_{PTAT} is much smaller than that in $V_{BE}(T)$ and needs no separate trimming.
The present author was involved in the design of temperature sensors that were trimmed on the silicon wafers, during testing of the chip. This was performed by adjusting the base-emitter voltage by changing the emitter area, and storing the result in a very small on-chip OTP memory. For this trimming a technology called Zener zapping is used.

Boundaries for accuracy

When, in the seventies and eighties of the last century, it was discovered that integrated circuits were suited to fabricate accurate voltage references and temperature sensors, scientist were looking for accuracy boundaries. In that time, it was not so easy to do experimental investigations for this with the required precision. Not only the performance of experiments, but also fabrication of good prototypes was sheer drudgery [7]. Yet, it was possible to find nonidealities of the precision devices, such as deviations in the PTAT voltage. Moreover, it was found that during thermal cycling, the device characteristics showed some hysteresis [7].
A smart student, named Peter Schmale, supposed that these nonidealities were due to the effects of mechanical stress. To check this, a setup was built (Fig. 3) in which a strip of silicon with bipolar transistors was bended to make a controlled mechanical surface stress [7]. These experiments showed that there was indeed a systematic effect of mechanical stress. Other scientist were already known with these so-called ***piezo-junction effects*** and knew that these effects were anisotropic and also dependent on crystal orientation and current direction.

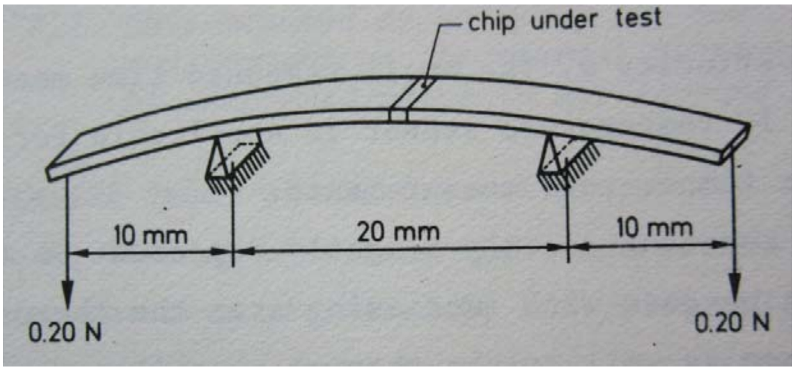

Fig. 3 Test set-up to determine the influence of surface stress for the base-emitter voltage of bipolar transistors.

It took about 15 years to find enough budget to start systematic research in that field. Two PhD students carefully investigated piezo-junction effects in bipolar transistors, for all directions of currents and mechanical stress, for all crystal orientation of silicon, and for both pnp and npn transistors.
One of the PhD students, Frederik Creemer, studied the physical phenomena up to the level of quantum mechanics. He concluded that that, similar to **piezo-resistive** effect, which is caused by conductivity changes of the **majority-charge carriers** in semiconductors, piezo-**junction** effect is caused by conductivity changes of the **minority-charge carriers.**
The other PhD student, Fabiano Fruett, developed and built an electro-mechanical setup for empirical research. With this setup he characterized all piezo-junction parameters. Next, these parameters could be used to calculate the effects of mechanical stress for base-emitter voltages.

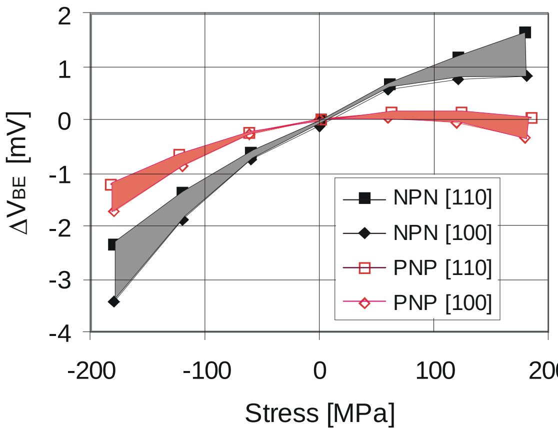

Fig. 4 Calculated stress-induced change in V_{BE} for the NPN and PNP vertical transistors for an arbitrary in-plane stress orientation; for a standard {001} silicon wafer [8] .

Some of the results are depicted in Fig. 4 ,which shows some very good news:

1) PNP bipolar transistors are less sensitive to mechanical stress than NPN ones
2) Such bipolar transistors can be manufactured in common low-cost CMOS technology, using vertical substrate transistors.

Today, many manufacturers apply this knowledge for the design of accurate integrated temperature sensors and bandgap-voltage references.

People interested in using these results of tiresome, laborious R&D work might feel happy that sometimes big problems are solved once and forever. However, this might also be disappointing for other people, such as those interested in doing R&D, now or in the near future. Because what is left for them to do?
For the latter group of people it might be good to note that with changing technology, new big problems will pop up and more-and-more researchers are needed to find solutions. In fact, technology is changing so rapidly, that it is impossible to find enough smart people who can do the R&D to fully apply the opportunities of all these new technologies.
To discover this, all over the world, research groups of universities and scientific institutes cooperate with a variety of companies, including very small company and very big ones.
From the big companies it can be learned that technology will not stop changing and how this will proceed in the future. From the small companies it can be learned how difficult it is for small companies to cope with that.

International Technology Roadmap

With respect to changing technologies, once per two years, an international group of companies published the International Technology Roadmap for Semiconductors (ITRS). The last revision of the ITRS Roadmap was published in 2013. Table 1 show a selection from the Critical Dimensions in semiconductor manufacturing processes, according to ITRS. This table also demonstrates some of the problems of small companies and universities to follow the ITRS roadmap. With respect to sensors, one main reason for this discrepancy is that the sensors are analog devices and that the new technologies are designed for digital circuits and often characterization and specifications for analog devices are lacking.

Table 1. Critical Dimensions (half-pitch) in semiconductor manufacturing processes, according to ITRS (International Technology Roadmap for Semiconductors): Since 1994, the critical dimensions were reduced with about a factor 3 per 6 years.

Year	CD according to ITRS in nm	CD in Smartec's temperature sensors in nm (year), [reference]
1982	1500	
1987	800	1500 (1988), [1]
1994	600	
1999	180	
2006	65	
2012	22	
2016	10	700 (2016), [9]
2018	7	
2020	5	180 (2022)

When analog functions should be implemented in digital circuits, huge problems will pop up with respect to budgets and work, for instance,

a) Characterization and specification will consume a large amount of additional R&D time and research capacity.
b) Using newest technologies is far too expensive for small companies and universities. For prototyping, MPW facilities are needed to share costs with other. Usually, after introduction of a new technology, it takes many years to organize MPW facilities.
c) Often new products should be compatible with previous and existing products. This is the case in, for instance, automotive and industrial applications. In new technologies the trend is to lower the supply voltages. Sometimes after the introduction of a new technology, modified technologies are developed in which the low-voltage components can be combined

with some high-voltage (HV) ones. However, this usually happens a long time after the introduction of a new technology.

Instead of focusing on the ITRS, for high-performance products, it is often better to focus on the remaining time that older technologies will be available. Usually, companies will not stop production as long there are enough clients. On the other hand, when with new technology digital circuitry should contain also some analog functions, such as monitoring the chip temperature, this might be possible for cases that high precision is not required. So, that even badly characterized components can be used and the signals can be processed with the low supply voltages of digital circuits.

High-performance temperature sensors

For the laboratory of Electronics laboratories of TU Delft the cooperation with the small company Smartec was important to learn more about the real problems of producers and users of sensors. As major results of this cooperation, over a period of 30 years, the scientists of the university have published many scientific papers and book chapters, while Smartec has fabricated or developed various high-performance versions of their smart temperature sensors. Table 2 lists highlights and biggest challenges of these temperature sensors.

Table 2. Highlights and challenges of high-performance temperature sensors, produced or to be produced by Smartec as a result of the cooperation with Delft University of Technology.

Introduction in / name	Techn.	Supply voltage	Temperature range	Highlights	Biggest challenges
1988 / SMT 160	BiCMOS	4.7V to 5.5V	-45 °C to 130 °C	- One of the first smart sensors, - duty-cycle-modulated output signal.	- Marketing of a new product, - on-wafer calibration.
2015 / SMT 172	0.7CMOS	2.7V to 5.5V	-45 °C to 130 °C	- Excellent resolution FOM: 3.2 pJK^2, - low packaging shift	- Implementation of CMOS analog circuits with high precision, - development of a small OTP.
future SMT 174/	0.18CMOS	1.6V to 5.5V	-45 °C to 130 °C	- Large Voltage range, - low supply voltage.	- Implementation of CMOS analog circuits with high precision for a low supply voltage, - development of a small OTP.

The sensors introduced in 1988 were produced in BICMOS technology and belong to the first smart sensors in the world [3]. A high accuracy was achieved by the applied on-wafer calibration.
The sensors introduced in 2015 were produced in CMOS technology [9]. Because in these sensors the npn transistors were replaced by pnp ones, the effects of mechanical stress are significantly reduced. For this reason packaging shift is minimal, while the long-term stability is excellent [9]. During development of these sensors, the main challenge was to design accurate analog circuits with badly matched CMOS components [10]. An interesting highlight of these sensors is the excellent resolution figure of merit (FoM) F, which deserves some explanation: In today's products the trend can be noticed to apply a growing number of sensors. The wiring of these sensors poses practical problems, because often the connections are not reliable enough, and often the sensors are installed in places where the use of wires is problematic.

Therefore, the interest in wireless sensors is increasing. For the same reason, there is an increasing demand to lower the energy consumption *E* per measurement. This energy consumption is related to sensor noise and standard deviation in the following way:
When the sensor output is a low-noise device, then already in a very short time it can produce a reliable output signal, and the shorter the time the lower the energy consumption. On the other hand, as will be shown below, for white noise and other random error sources, their effects will decrease with the square root of the measurement time. However, for a given power, the energy consumption is proportional to the measurement time.
This coherence in desired properties is expressed in the resolution figure of merit (FoM) *F*, which for temperature sensors is defined as:
$F = E \cdot s^2$ (unit: JK^2),
where *E* is the energy consumed during one complete measurement (unit: J) and
s is the sensor's resolution (standard deviation in K).

In CMOS transistors in addition to white noise, there is a relatively strong 1/*f* noise. The influence of 1/*f* noise doesn't decrease for longer measurement time, because of the wider bandwidth for low frequencies. Fortunately, this type of noise can be eliminated by using circuit techniques, such as chopping and dynamic element matching. These techniques have been applied in the SMT 172 sensor. To check whether or not these techniques work properly, the noise performance of the sensor has been measured for the range of the shortest measurement time of 2 ms up to about 2 s (Fig. 5). The measurement times were increased by repeating the measurements continuously and averaging the measurement results. The blue line in Fig. 5 depicts the measurement result, which shows that the resolution indeed improves proportional to the square root of the measurement time (depicted by the dotted red line). Especially, for the long times, performing such measurements is very difficult. For these long times, the extreme low-noise has to be distinguished from possible fluctuations due to minor temperature changes. For details about the applied measurement methods, interested readers are referred to [11]. More details about the sensor and its application can be found in [9] and [12].

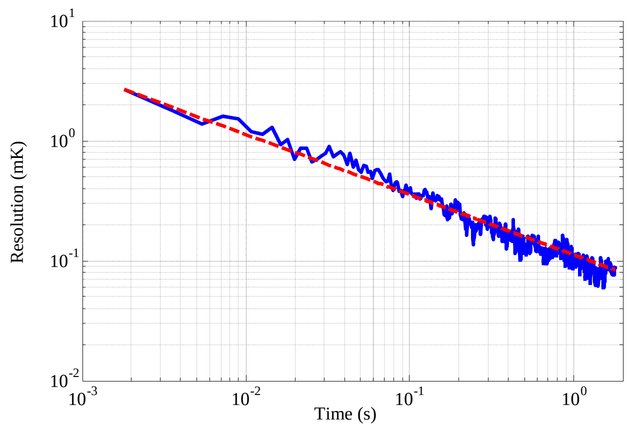

Fig. 5 The measured resolution (standard deviation) versus the total measurement time.

Discussion and Conclusions

Thanks to smart young scientists, inspired staff members and entrepreneurs, universities and small companies can deliver a huge contribution to extend scientific knowledge, which is so important for innovation of industry and society. In most cases, breakthroughs and other significant contributions are the result of careful observations and analysis of smart experiments.

In this paper this is demonstrated by analyzing the work flow over a period of 40 years on the specific topic of designing novel thermometers, and thermal sensors.
In the 18the century, Faraday invented and started production of mercury thermometers, using the best opportunities of the glass technology offered in his time. Nowadays, large progress is made in the development of thermometers using the best opportunities of semiconductor technology.
In no other parts of society, technology is changing so fast as in the semiconductor industry. This is due to the agreement and cooperation between large international groups of companies, such as those who published the International Technology Roadmap for Semiconductors (ITRS).
In semiconductor technology, digital circuits are the moneymakers. Therefore, the rapid progress in technology is driven by the needs for more and smaller digital circuits. These needs are smaller dimensions (and less costs) per component, more components per chip, lower supply voltages and lower energy consumption per component. In addition to the digital circuits also some analog circuits and devices are needed, such as temperature sensors that monitor the chip temperature and other sensors needed to improve reliability and lifetime, or to optimize the functionality being important for innovation of the products.
Usually, even for big companies, it is difficult to find enough R&D capacity to characterize components for analog design and to develop analog circuits for each technology generation. As shown in this paper, university and small companies can deliver a good contribution in this field. However, this work can only be done when prototypes can be made and tested. Because of the high expenses of full wafer production, participation of universities and small companies requires that the costs can be shared, for instance by offering facilities for the production of multi-projects wafers.
For lovers of R&D, the good news is that there is always too much work to do. So they can feel themselves encouraged to do what they like most and what fits the best with their capacity.

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