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Procedia Computer Science 83 (2016) 863 – 869

Procedia Computer Science

The 6th International Conference on Sustainable Energy Information Technology (SEIT 2016)

Regular Bulk CMOS Hall Effect Sensors Employment in Solid-State Power and Energy Meters

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Abstract

This paper is intended to present an advanced technique to be used in solid-state power and energy meters, more specifically through the employment of the Hall effect sensors. From a qualitative point of view, an investigation into the sensing device is performed and geometrical consideration of the Hall cells onto the performance is analyzed. Different Hall cells (basic, L, XL, borderless and optimum) have been fabricated in a regular bulk CMOS technology and their main parameters were extracted. To this purpose, experimental results for the offset and sensitivity of different Hall cells are obtained. The dissipated power as well as the power-related sensitivity is calculated, for the five Hall cells in discussion.

Keywords: Hall sensors; power meter; energy meter; offset; sensitivity

1. Introduction

The world is experiencing a huge demand for energy nowadays. Having the proper tools to measure it, is essential. As we know, the electricity meters are used to measure the amount of electric energy consumed by any electrically powered device. Solid-state meters have been in huge demand lately, owing to their higher accuracy, low cost and robustness[1]. Fully integrated systems that are able to provide energy and power measurements are overtaking the classical, old age, electrochemical meters. This paper is intended to present the employment of the Hall effect sensors in the realization of integrated power and energy meters, as well as to analyze from a device point

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doi:10.1016/j.procs.2016.04.177

of view, the geometrical influence of the Hall cell onto the performance of the system, in terms of sensitivity and offset. The PhD thesis[2] as well as the previous papers of the author[3] were concerned with the analysis of the geometrical influence of the Hall cells on the performance of the current sensors. In these studies, the work of the author was focused on analyzing in details the offset and offset temperature drift of the Hall cells and identified the geometry that needs to be chosen in order to guarantee a minimum offset and high sensitivity. Both regular bulk[2,3] and non-fully depleted Silicon on Insulator Technologies[4] have been employed in the fabrication of Hall cells, by the author. Temperature effects onto the current-related sensitivity of the Hall cells, including freeze-out effect, were studied by the author[5,6].

The paper is structured in the following way. Section 2 talks about the use of Hall sensors in power and energy meters, touching upon the suitability of Hall sensors for current sensing in electricity meters and presenting the power measurement principle using the Hall sensors. A small discussion of the time suitability of Hall sensors in energy meters is also made at this point. Section 3, devoted to the results and discussion, is intended to present the considerations of geometry influence onto the performance of Hall cells, and introduces the main parameters of five different Hall cells which are studied (Basic, L, XL, Borderless and Optimum). Additionally in the third section, the main results of the power dissipation and power-related sensitivity are presented for the five Hall cells. The final section dedicated to the conclusions, summarizes the performance of the analyzed Hall cells and proposes the next perspectives to this work.

2. Use of Hall sensors in energy meters

Hall Effect sensors are used in a multitude of industrial applications ranging from current sensing in the automotive industry to measurements of mechanical quantities such as position or angle, in DC motors, tachometers, etc. They have been also employed for direct magnetic field sensing, as in electronic compasses[2,7]. Some applications employing Hall effect sensors, such as direct field sensing, contactless current sensing or power measurements, require increasingly accurate measurements.

Recent studies were concerned with the use of Hall sensors in electricity meters. A fully integrated SOI Hall sensor based solid-state meter for power and energy measurements with dynamic offset cancellation was introduced[8,9]. The proposed microsystem had low power consumption and full integration on a single chip. An SOI 0.6 mV offset temperature-compensated Hall Sensor readout IC for automotive applications up to 200°C was reported[10]. There are different ways to implement solid-state electricity meters, leading to different system performances[11].

One of them is a Hall sensor based solid-state meter[12] that offers possibility of current sensing and current - voltage multiplying at the same time. Moreover, the main advantage of the Hall effect device is that it can be integrated together with a circuitry performing signal conditioning functions on the same chip. In that way, low cost, high resolution, fully integrated solid-state meters for power and energy measurements can be realized using a standard technology[8,9].

2.1. Time-stability of Hall Effect sensors in electricity meters

The Hall effect sensors have been used for current sensing in electricity meters. Regarding the subject discussed here, a small contradictory state has already appeared. Although the engineering practice of Hall cell development has been to achieve stable offset characteristics, for the largest single market for Hall devices this parameter is somewhat irrelevant. A pertinent analysis shows that only two parameters are critical in the device functionality. Undoubtedly they are the Hall sensitivity temperature coefficient and, respectively the Hall sensitivity ageing coefficient[13].

Particularly, a Hall effect device is characterized by the Hall voltage V_{HALL}. Therefore, for the Hall cell, the differential Hall voltage is given by:

$$V_{HALL} = G\mu\left(\frac{W}{L}\right)RI_{bias}B \quad (1)$$

where G is the geometrical correction factor (less than or equal to unity), I_{bias} is the biasing current, μ is majority carrier mobility, (W/L) is the width/length ratio of the strip, R is the electric resistance of the strip and B is the magnetic field induction[13].

Observing equation (1) for the Hall potential, for constant biasing current I_{bias} from a source invariant to temperature, it results that the sensitivity $S_A = V_{HALL} / B$ will not change considerably with the variation of the temperature. By looking again at the sensitivity equation, we can infer that both a stable resistance value for R and a dimensionally stable Hall cell will produce a long-term stability. The 25-year requirement for an electricity meter does not constitute a problem due to the fact that data on accelerated ageing test is provided by manufacturers for a large time interval[13]. Therefore, we can conclude that the Hall effect devices are recommended for current sensing within AC power calculators, and have been now employed in such applications for a long time.

A study of the temperature variation of the Hall cells current-related sensitivity has been performed by the author in details[5], for different Hall cells, fabricated in a regular bulk CMOS process. The magnetic sensitivity temperature dependence of the Hall cells is influenced by the temperature variation of two competing factors namely the freeze-out effect of the electron density and the Hall scattering coefficient respectively. As proven, this results in a second order parabolic dependence of the current-related sensitivity with the temperature[5].

2.2. Power measurement principle using Hall effect sensors

In relation to the use of the Hall sensors in energy and power solid-state meters, the next equations should be considered. As it is already known[14], the Hall-sensor output voltage is given by:

$$V_{HALL} = S_A B = S_I I_{bias} B \tag{2}$$

where S_A is the absolute sensitivity, S_I represents the current-related sensor sensitivity, I_{bias} the sensor bias current, and B the magnetic induction proportional to the line current i_{line}. The sensor bias current I_{bias} is obtained from the line voltage v_{line} using a high value resistor R_{bias}, i.e., $I_{bias} \propto v_{line} / R_{bias}$. Looking at equation (2) gives us a very rapid idea on what the principle of using Hall effect sensors in power measurement is.

If the current is held constant, the Hall voltage is proportional to the measured power line voltage v_{line} and current i_{line}, and therefore $V_{HALL} = f(v_{line} i_{line}) = c \cdot v_{line} \cdot i_{line}$. Considering a trigonometrical form for the line voltage $v_{line} = V_m \cdot \cos\omega t$ and for the line current $i_{line} = I_m \cdot \cos(\omega t + \varphi)$, the Hall-sensor output voltage could be simply rewritten as:

$$V_{HALL} = c \cdot V_m \cdot \cos\omega t \cdot I_m \cdot \cos(\omega t + \varphi) = c \cdot V_m \cdot I_m \cdot \cos\varphi + c \cdot V_m \cdot I_m \cdot \cos(2\omega t + \varphi) \tag{3}$$

where c is the constant of the meter transduction and φ is the phase between the line current and line voltage[9]. In equation (3) above we can recognize two terms. The first term of the addition in this equation corresponds to a DC voltage, which contains the power to be measured $V_m I_m$, which will be subsequently used for the calculation of the energy. On the other hand, the second term contains the AC voltage.

2.3. Schematic diagram of power meters using Hall effect sensors

Figure 1 presents the basic diagram of the use of Hall sensors in power meters. A solid-state meter using Hall sensors offers two simultaneous advantages, namely the measuring of the current and the multiplication of current and voltage[12]. The overall integrated circuit, which is used to obtain the energy readout, will contain the Hall sensor, the mixed mode electronics and the analog to digital converter block[9]. The Hall sensor can be fabricated in a regular bulk CMOS or Silicon on Insulator (SOI) technology.

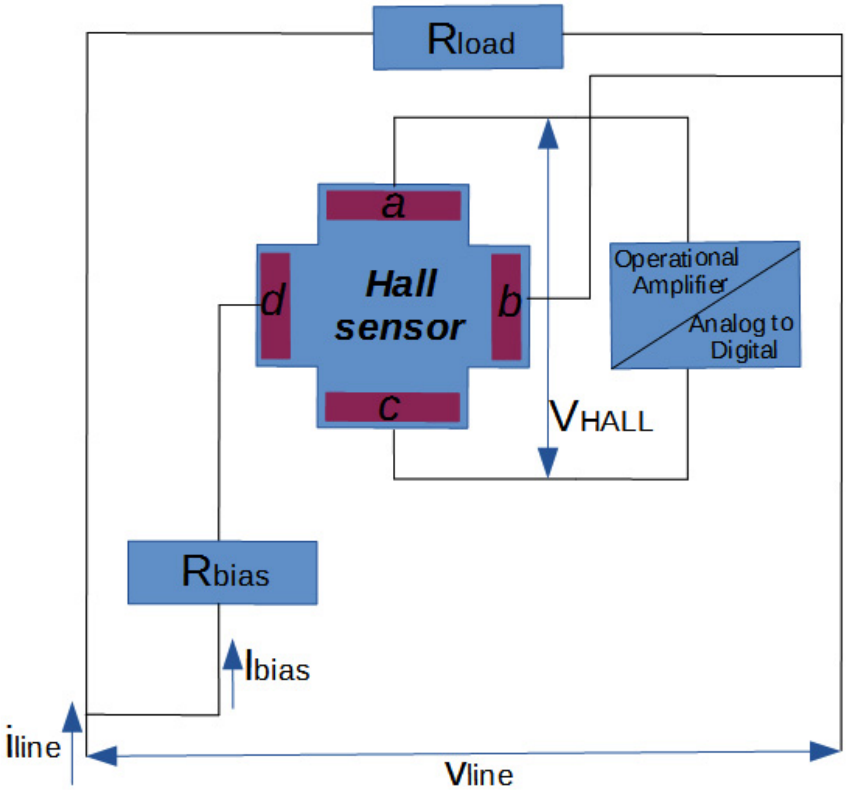

Fig. 1. The schematic diagram of the power meter system using Hall sensors.

3. Results and discussion

3.1. Geometrical influence of the Hall device onto the sensing part

To the purpose of seeing how the geometry affects the performance of the Hall sensors, five different structures in regular bulk CMOS technology, namely Basic, L, XL, Borderless and Optimum Hall cells have been analyzed. In Figure 2, the geometries of these different Hall cells are depicted. Both Greek cross cells and square cells have been fabricated. The basic Hall cell was chosen as reference, while L and XL are scaled up version of the basic cell by ratios of 1.5 and 2 respectively. The Borderless shape has the sensing contacts located farther away from the p-n junction and more to the inner part of the n-well, so it could help in minimizing any errors that might appear on the borders. However, in this case, the sensitivity is reduced. The Optimum Hall cell is a combination of increased size and contacts located at an optimum distance between the cells borders and the middle of the active region.

Selection of the optimal geometry for a current sensor is made on different criteria namely sensitivity, offset, dissipated power, etc.

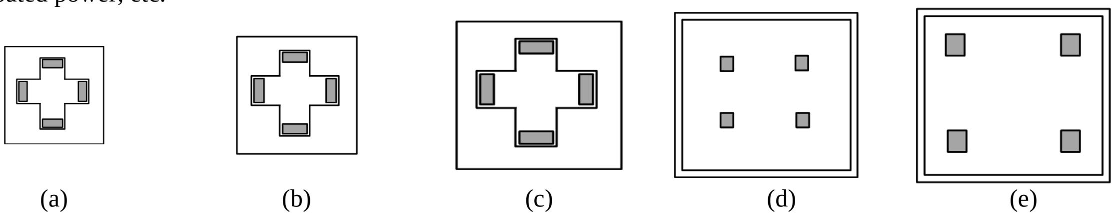

Fig. 2. The structures of the Hall cells, Basic (a), L (b), XL (c), Borderless (d), Optimum (e).

The next table presents the geometrical dimensions of the five Hall cells, which have been considered for discussion. The Hall cells length, width and contacts dimensions are included.

Table 1. Hall cells geometrical dimensions.

Geometrical structure	Length L (μm)	Width W (μm)	Contacts s (μm)
Basic	21.6	9.5	8.8
L	32.4	14.25	13.55
XL	43.2	19	18.3
Optimum	50	50	4.7
Borderless	50	50	2.3

3.2. *Hall cells main parameters*

The five Hall cells have been measured for their main parameters. In Table 2, numerical values of the input resistance R_{in}, absolute sensitivity S_A and offset temperature drift are presented. A dozen different samples of the same Hall cell have been measured.

Table 2. Hall cells main parameters.

Geometrical structure	R_{in} (kΩ)	S_A (V/T)	Offset drift (μT/C)
Basic	2.3	0.082	0.409
L	2.3	0.082	0.264
XL	2.3	0.082	0.039
Optimum	1.8	0.064	0.0526
Borderless	1.3	0.032	0.328

3.3. *Hall cells dissipated power calculation*

As was presented by the author in her PhD thesis[2] and recent papers, three dimensional physical models have been developed, using Sentaurus Synopsys software[15], in order to obtain numerical values for the Hall cells parameters of interest. For the complete analysis of the magnetic Hall sensors behaviour, we have used the physical simulations of the magnetic field effect onto the semiconductors. As it is of great interest for our present study, investigation into the Hall cells dissipated power were performed. Taking into account the fact that the power is the rate at which energy is expended, there is a direct relation between the energy and power through time, the same type of graphs like in Figures 3-4 can be obtained for the energy.

The Hall voltage can be expressed as a function of the power dissipated P within the devices[14] such as given by the following relationship:

$$V_{HALL} = G\left(\frac{W}{L}\right)^{1/2} r_H \left(\frac{\mu}{nqt}\right)^{1/2} (P)^{1/2} B \tag{4}$$

where G is the geometrical correction factor, W and L are the width and length of the Hall cells respectively, r_H is the Hall scattering factor, μ is the mobility, n is the carrier density, q is the elementary charge, t is the thickness of the active region and B is the magnetic field induction[14]. In the case of silicon, r_H is usually 1.15.

The dissipated power was calculated against the biasing current, for the five Hall cells, through simulations and the data in Figure 3 is obtained. We can see that the lowest dissipated power is of Borderless Hall cell, with a power of around 1.5 mW, for a biasing current of 1 mA.

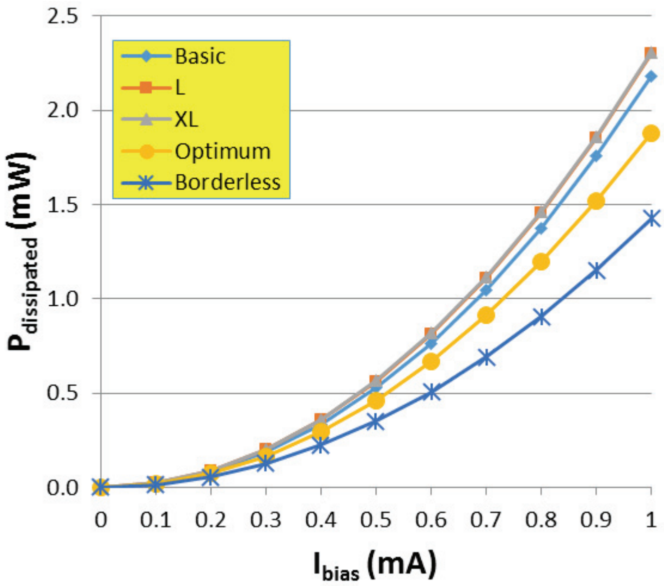

Fig. 3. The dissipated power versus biasing current, for the five different Hall cells.

Additionally, we were interested to investigate the power-related sensitivity versus the dissipated power, as it can be seen in Figure 4. The power-related sensitivity S_P measured in V/WT is a relative measure, which can be defined as the ratio between the absolute sensitivity and power, more specifically $S_P = \frac{S_A}{P}$. We can observe that the borderless has the lowest power-related sensitivity, while the other four Hall cells present almost the same value for this quantity.

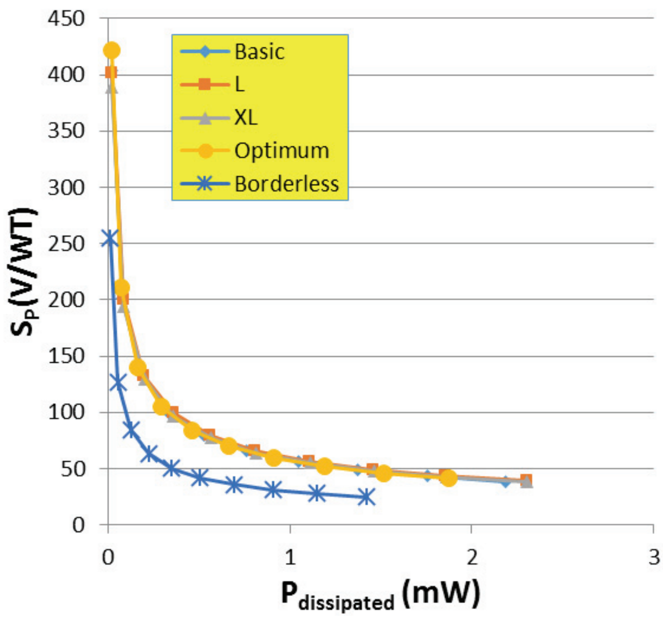

Fig. 4. The power-related sensitivity versus power dissipated, for the five different Hall cells.

4. Conclusions and future perspectives

The current work was intended to present performance consideration on different types of Hall cells to be employed as Hall current sensors, for power and energy measurements. To this purpose, five different Hall cells (basic, L, XL, Borderless, and Optimum) have been analyzed. Experimental results regarding their main parameters including input resistance, sensitivity and offset temperature drift have been provided.

In order to see the influence of the device geometry on the overall performance, investigation into the dissipated power and power-related sensitivity has been made. We observed that the lowest dissipated power was provided by the Borderless Hall cell, with a power of around 1.5 mW, for a biasing current of 1 mA. Borderless has also the lowest power-related sensitivity, while the other four Hall cells present almost the same value for this quantity.

As there is a direct relation between the energy and power through time, the same type of graphs can be obtained for the energy consumption investigation for time intervals of interest.

The next objective is to do the same type of investigation for Silicon on Insulator Hall cells, which have been integrated recently by the author in a non-fully depleted SOI technological process.

Acknowledgements

The author, Maria-Alexandra Paun, wishes to thank the Swiss National Science Foundation (SNSF) from Switzerland for the promotion and encouragement of the scientific research of young doctors, respectively by providing the funding for her advanced postdoctoral fellowship at Cambridge University, UK and the return phase at Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland.

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