Piezo-Hall Characterization of Integrated Hall Sensors Using a Four-Point Bending Bridge

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Abstract

This paper reports on the characterization of the stress-dependent magnetic sensitivity of CMOS-based Hall devices, i.e. cross-shaped four-terminal n-wells and field effect transistors (FET) with four source-drain contacts, using a novel experimental setup. The setup comprises a four-point bending bridge used to apply well-defined mechanical in-plane stress to silicon strips, combined with permanent magnets for the application of controlled magnetic fields up to ±240 mT. Measurements of both n-well-based Hall plates and FET-based Hall plates are performed. The piezo-Hall coefficient $P_{12}$ extracted from stress measurements under vertical magnetic fields from the n-well sensors is in excellent agreement with previously reported values while the FET-based devices exhibit a clearly reduced coefficient.

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1. Introduction

The analysis of the influence of mechanical stress on the performance of integrated circuits and sensor systems such as Hall sensors gains growing attention in industrial applications. Mechanical stress acting on the integrated circuits may result from packaging processes due to the different thermal expansion coefficients of the applied materials or from variable ambient operating conditions. In case of Hall sensors serving to determine magnetic fields, the mechanical stress first causes an offset signal that can be compensated by the current spinning method [5] and modulates the sensitivity of the Hall device. This sensitivity change is referred to as piezo-Hall effect [1]. In view of a compensation of this effect during sensor operation it is of great interest to quantify it [2]. This paper focuses on the characterization of the piezo-Hall coefficient $P_{12}$. This coefficient describes the change in Hall sensitivity due to in-plane normal stress ($\sigma_{xx} + \sigma_{yy}$) [1]. The paper compares the extracted coefficients of n-well-based and FET-based Hall sensors.
2. Experimental setup

One possibility to characterize the piezo-Hall effect of integrated Hall sensors consists of applying a uniform in-plane stress to the device under test. Typically, this test is performed on a tensile test setup necessitating an appropriate clamping of the test samples and relatively large forces [1]. The tensile setup is combined with an electromagnet [1]. In contrast, this study applies a four-point bending bridge setup (4PBB) combined with permanent magnets to apply in-plane stress to silicon beams cut from standard 6-inch CMOS wafers. Although 4PBB setups are well-established tools for mechanical characterization of integrated circuits [3, 4], they have not been used so far in piezo-Hall measurements.

The 4PBB setup applied in this study is schematically shown in Fig. 1 (a). It comprises fixed outer supports and inner supports attached to a force sensor translated in the $z$-direction using an automated stage. The silicon strip with the test sample, wire-bonded to a printed circuit board (PCB), is placed between the inner and outer supports. The bond wires exert a negligible parasitic mechanical stress. In order to apply magnetic fields vertical to the surface of the silicon beam, the 4PBB is equipped with a stack of standard neodymium permanent magnets positioned above the silicon strip using a PVC housing. As illustrated in Fig. 1 (a), the housing is fixed on the PCB which is translated in parallel with the inner supports using the z-stage. A photograph of the setup is shown in Fig. 1 (b).

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**Fig. 1**: Modified 4PBB with permanent magnets mounted above a silicon strip exposed to mechanical stress; (a) schematic illustrating the magnetic field lines of the permanent magnets and (b) photograph of the setup.

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**Fig. 2**: Distribution of the vertical magnetic field component $B_z$; (a) Contour plot of $B_z$ at a distance of $z = -16$ mm from the magnet stack and (b) magnetic field $B_z$ and relative change $(dB_z/dz)/B_z$ in the center, indicated by X, as a function of distance $z$ from the magnets.
By changing the vertical position of the magnets in the housing using spacers, the magnetic field \( B_z \) to which the sensor is exposed can be varied in discrete steps between 30 mT and 240 mT. Further, inverting the orientation of the stack of magnets results in magnetic fields of opposite sign. As the magnetic field of these permanent magnets is inhomogeneous with respect to the lateral and vertical direction, a relative translation \( \Delta z \) of the sensor with respect to the supports and the corresponding deformation \( d_{FS} \) of the force sensor. According to beam theory, the beam is bent by \( b_{\text{beam}}(F) = \frac{3FL_o^2Eh^3}{bEh^3} \), where \( F \), \( L_o \), \( E \), \( b \), and \( h \) denote the applied force, outer and inner distances of the supports (cf. Fig. 1 (a)), Young’s modulus of silicon, as well as the width and thickness of the beam, respectively. The deformation \( d_{FS} \) of the force sensor is related to its stiffness \( S_{FS} \) through \( d_{FS}(F) = F/S_{FS} \).

In order to compensate for this effect, the spatial distribution of the vertical magnetic field component \( B_z \) was characterized. Figures 2 (a) and (b) show the lateral distribution and vertical development of \( B_z \), respectively. At an applied normal stress \( \sigma_{n} = 100 \text{ MPa} \) corresponding to an applied force \( F = 7 \text{ N} \), the relative movement \( \Delta z \) is typically 76 μm. This movement results in a relative change in \( B_z \) of about 0.7%, which is compensated during the measurements.

3. Measurements

Measurements were performed using cross-shaped four-contact n-wells and FETs with four source/drain contacts fabricated in a commercial 0.6-μm CMOS technology. Both, n-well and n-FET structures have the same geometry. Micrographs of both sensors are shown in Fig. 3. The n-well devices are current biased using \( I_{bias} = 2.5 \text{ mA} \) while a gate voltage and source-drain current of \( V_{\text{Gate}} = 5 \text{ V} \) and \( I_{DS} = 275 \mu\text{A} \), respectively, were applied to the n-FET devices. The applied \( I_{DS} \) values are close to the maximum current of 300 μA at the chosen gate voltage. In order to cancel out the influence of in-plane shear stress from the Hall signals, we employed four-fold current switching [5] by rotating the applied input current in steps of 90° and adding up the corresponding Hall signals.

![Fig. 3: Optical micrograph of the Hall sensor devices; (a) n-well sensor and (b) FET-based sensor.](image1)

![Fig. 4: Measurement results of the n-well device at an input current of \( I_{bias} = 2.5 \text{ mA} \); (a) measured Hall signal after four-fold current spinning as a function of the applied stress \( \sigma_{n} \) at \( B_z = 240 \text{ mT} \) and (b) Hall signal and corresponding linear fits as a function of the applied magnetic field \( B_z \) at two stress levels of \( \sigma_{n} = 0 \text{ MPa} \) and \( \sigma_{n} = 100 \text{ MPa} \).](image2)
Figure 4 (a) shows the measured Hall voltage $V_{out}$ of an n-well device after four-fold current spinning as a function of the applied mechanical stress $\sigma_x$, at an applied magnetic field $B_z = 240$ mT. Figure 4 (b) shows the resulting Hall voltage as a function of $B_z$, at stress levels of $\sigma_x = 0$ MPa and $\sigma_x = 100$ MPa, normalized to the input voltage corresponding to the applied bias current. The sensitivity of the device is evaluated from the slope of the linear fits of the measured data shown in Fig. 4 (b). For the n-well device, it is found that the relative sensitivity change is about 3.7% at $\sigma_x = 100$ MPa, resulting in a piezo-Hall coefficient of $P_{12} = (37 \pm 1) \times 10^{-11}$ Pa$^{-1}$. As the n-well doping concentration is about $2 \times 10^{16}$ cm$^{-3}$, this result is in excellent agreement with previously reported values [1].

As the current is much lower for the n-FET devices compared to the n-well devices, the absolute sensitivity is also lower by almost a factor of 6. Figures 5 (a) and (b) show results of an n-FET device. It is found that for the n-FET devices, the sensitivity change has the opposite sign and a lower absolute value than that of the n-well device, resulting in a piezo-Hall coefficient of $P_{12} = (15 \pm 0.7) \times 10^{-11}$ Pa$^{-1}$. The dependence of this coefficient on the biasing conditions remains still to be evaluated.

4. Conclusion

This paper reported on the piezo-Hall characterization of integrated Hall devices. The experimental setup employed consists of a 4PBB setup and permanent magnets which allow for the application of mechanical in-plane stress up to $\sigma_x = 140$ MPa and magnetic fields $\pm B_z$ between 30 and 240 mT. The change in $B_z$ due to relative beam displacement within the inhomogeneous $B_z$ field was taken into account. Piezo-Hall coefficients $P_{12}$ of both n-well based and n-FET-based Hall devices were extracted. For the n-well sensors, $P_{12} = (37 \pm 1) \times 10^{-11}$ Pa$^{-1}$. For the n-FET sensors, the extracted piezo-Hall coefficient is clearly reduced and has the opposite sign, with $P_{12} = (15 \pm 0.7) \times 10^{-11}$ Pa$^{-1}$.

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