特別寄稿

INTEGRATED MAGNETIC SENSORS : AN OVERVIEW

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Abstract

The basic physical principles involved in the operation of monolithic magnetic sensors are reviewed and technological aspects outlined. More or less conventional devices based on Hall effect, magnetoresistance or current path deflection are described. It is shown that such sensors with 2, 3, 4 or 5 terminal contacts are achievable with standard silicon integrated circuit process. Several kinds of magnetodiodes (p^+nn^+,p^+n, Schottky, MOS, memory, CMOS) have been fabricated on Si and on SOS films and present attractive properties. Finally, the magnetotransistor family is discussed with emphasis to split-terminals, CMOS, unijunction and filamentary devices.

I. Introduction

The vertigineous growth rate of microelectronics could probably not be kept up in the future by only increasing the complexity of the integrated circuits, based on the reduction of MOSFETs dimensions and the enlargement of chip size. New devices with original functions must be conceived to allow the colonisation of new domains by the integrated circuit production. Magnetic sensors are in this respect very good candidates for new applications.

The accurate measurement of *weak fields* is fundamental for progress in geophysics, magnetic bubble technology, magnetometry, magnetic cards, signal recognisation, medicine, etc. The detection of small *variations* of a magentic field is, on the other hand, useful for navigation, orientation, mineralogic prospection and volcanology (via the assessment of surface fluctuations of the earth field), control of strong currents stability, magnetic switching, etc. In addition, magnetic sensors can *indirectly* detect other signals (mechanical, optical, chemical) which are able to disturb the behaviour of a referenced magnetic field. Actual applications consist in the control of (rotating) mechanical systems, motor regulation, pressure and position measurements, angle and proximity detection, etc.

The integrated magnetic sensors make these applications cheap enough to fit wide public fields; considering ten sensors used in a car (for engine and wheel control) gives an order of magnitude of the total number of equivalent components consumed in a year for *only one* application. Other advantages of monolithic

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sensors comes from the obvious possibility to achieve *in situ* signal processing (amplification, offset and temperature compensation, noise reduction, etc.).

The conception of integrated magnetic sensors is, however, not straigtforward since silicon is not a magnetic material and presents poor carrier mobility. Moreover, silicon is very sensitive to mechanical and temperature variations, which give parasitical signals in case of magnetic detection. This explains why, at present, there is no device able to meet all requirements, although many types of silicon transducers have been proposed. The physical approaches are in fact restricted to the consequences of the Lorentz force (Hall effect, magnetoresistance, carrier deflection). Gains in sensitivity have been recently obtained by incorporating additional effects of surface recombinations, carrier injection modulation and filament formation.

In this paper the most prominent devices will be systematically described with emphasis to the physical principle of operation. Technological refinements proposed to achieve a better fit between the basic constraints of these components and the Si material capability will be also outlined.

II. Conventional Sensors

1. Hall devices

A typical Hall device (Fig. 1a) has two longitudinal ohmic contacts for current supply and two lateral contacts for Hall voltage measurement. When a transverse magnetic field B is applied, flowing electrons are submitted to Lorentz forces and very fast carrier accumulation occurs on the sample sides. This accumulation stops when the induced electric field, called Hall field, balances the Lorentz force effect. To achieve a strong Hall field requires materials with high carrier mobility and for this reason InSb was traditionally used. As the Hall voltage is proportional to the width of the sample (which must be also "long" to prevent end short-circuits), problems arise from the large size of Hall integrated sensors.

At constant current the Hall voltage increases as the sample thickness is reduced. This condition can be fulfilled in thin silicon on insulator films or in n-type homoepitaxial layers grown on p-type substrate, prior to conventional bipolar circuit process [1]. The careful optimisation of doping and dimensions takes into account various criteria: maximum values of current, voltage and power, offset tolerance, sensitivity [2] and noise [3].

Silicon Hall sensors are very linear but, in turn, exhibit modest sensitivities (below 1 V/T, after amplification, for commercially available devices). According to Van der Pauws extentions other configurations can be used (Fig. 1b).

2. Magnetoresistance sensors

The magnetoresistance effect is the dual of the Hall effect since it becomes important when carrier deflection occurs, i.e. when the Hall field is suppressed. Under the effect of Lorentz forces the average drift path of carriers across the sample becomes longer and causes the apparent mobility to decrease and the sample resistance to increase.

The Hall voltage can be short-circuited by incorporation of metallic needles (NiSb, FeSb) in the sample volume or by photolithographic formation of fine Al lines across the surface. An *internal* reduction of the Hall field occurs in mixed semiconductors where the electron and hole contributions to the Hall effect are opposite and can compensate each other; nevertheless, the preparation of near intrinsic Si is not a realistic issue. More attractive is the use of geometrical effects. In a wide but short sample (Fig. 1c) the Hall field could not reach its maximum value due to the proximity of equipotential end contacts and, therefore, a geometrical magnetoresistance occurs. The limited case of this shortened geometry is represented by the Corbino disk (Fig. 1d) where the Hall field is zero and the geometrical magnetoresistance is a maximum ($R_B \sim 1 + \mu^2 B^2$).

It is obvious that the condition of high carrier mobility becomes even more stringent for magnetoresistance than for Hall sensors and disqualifies silicon. Furthermore, as the sen-

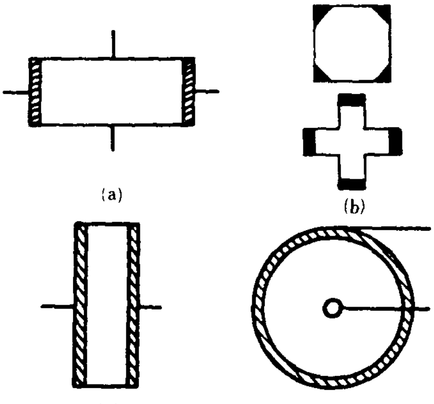


Fig. 1. Configuration of several conventional sensors: Hall (a), Van der Pauw (b), geometrical magnetoresistance (c) and Corbino disk (d).

sitivity is rigurously null around B = O, the magnetoresistor must be associated with a permanent magnet (B_O) in order to translate the detection around B_O.

A different type of magnetoresistance acts in ferromagnetic materials where the magnetisation vector rotates under the influence of an external magnetic field [4]. NiFe permalloy films 200 Å thick exhibit few percent change in resistance and have a number of interesting applications, but this does not concern Si until these films are deposited on Si wafers.

3. *Three terminal devices*

A three terminal device (Fig. 2a) is based on the combination of Hall and magnetoresistance effect. The application of a perpendicular magnetic field involves a lateral deviation of current lines and, therefore, induces a dissymmetry in the currents flowing across the two sensing terminals; the current difference is then converted into a voltage by the addition of load resistors on these branches. An optimised geometry consists in a short length ($L < W$) to increase the geometrical magnetoresistance and moderate distance between contacts ($x \approx L$) to accentuate the dissymmetry. The interest of two-dimensional modelling and relevant results have been outlined by Baltes and Popovic in an excellent review paper [5].

A different configuration was proposed for the case where all the contacts must be situated on the same side of the plane [6], which is particularly useful for *vertical* sensors integrated in bulk Si. The three terminal device can be transformed into a five-terminal device (Fig. 2b) by addition of separate sensing Hall contacts. Such a device was realised with the standard CMOS technology, which offers the possibility to isolate the active n-type volume from its surroundings by a reverse-biased pn junction (p-well) [7].

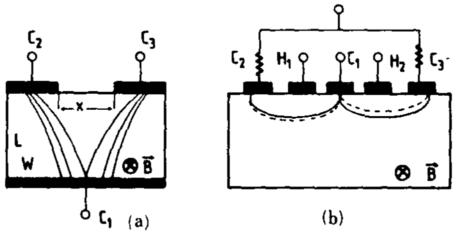


Fig. 2. Horizontal three-terminal Hall effect device (a) and vertical five-terminal sensor (b) integrated on Si [6]

III. MOS Hall Devices

An interesting alternative to meet the constraint of a "thin" Hall plate is given by MOSFET devices, the inversion channel of which is as thin as 100 Å. Another advantage is, in this case, the use of the standard CMOS technological process.

1. *Four-terminal MOSFET-Hall sensors*

The basic device is a large n-type (enhanced mode or depletion mode) MOS transistor which has two additional lateral contacts (Fig. 3a). These Hall probes are implanted simultaneously with the source and drain regions. Operated in the linear regime, the MOS-Hall device behaves as an ohmic Hall plate but provides little Hall voltage. In the saturation regime, the longitudinal field distribution is no longer uniform giving rise to a higher Hall field closer to the drain region. Moreover, shunting effects are strongly reduced near the drain due to a higher resistivity than close to the source. An optimised depletion-mode device has square-type geometry ($L \approx W \approx 500\ \mu m$) with sensing contacts situated at about L/4 distance from the drain. Operated in the triode region ($V_G = V_D = 5$ V), it shows a sensitivity $S'_V = \Delta V / V \Delta B$ of about 0.06 T^{-1}, an offset of 14 mT and a good linearity below 0.1 T [8].

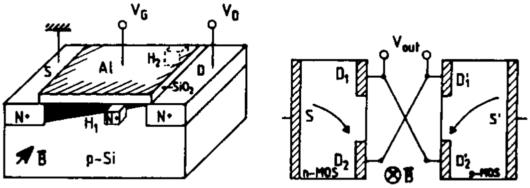
2. *Speical MOS-Hall devices*

A MOS-Hall sensor *free* from short-circuit effects has been achieved by replacing the low resistance source and drain regions by "distributed current sources" with extremely large resistivity [9]. This device behaves as if it was infinitely long, although its length is very short ($L = 10 \mu m$, $W = 100\ \mu m$) enabling the formation of high electric fields. In these short devices, hot carrier effects occur and make the sensitivity be governed by the carrier satuation velocity; silicon is no more disadvantaged because, unlike the mobility, the saturation velocity depends only slightly on the material. Devices fabricated with standard double poly-Si gate CMOS technology exhibit a sensitivity $S_V = \Delta V / \Delta B$ of about 1 V/T.

Based on the principle of three-terminal sensors, *split-drain* MOSFET devices were conceived (Fig. 3b). Two or three adjacent drain regions share the current. The current flow deflection caused by the magnetic field induces a dissymmetry in the drain currents. Loading the drains with high resistances gives a differential voltage [10]. An interesting improvement was obtained by the complementary association of dual-drain sensors. The drain with increasing current of the n-channel transistor is connected to the drain with decreasing current of the complementary p-channel transistor and vice-versa. This cross-coupling allows low power dissipation, good stability and sensitivity of 1.2 V/T [11].

IV. Magnetodiodes

Magnetodiodes are devices with mixed conduction where the electron-hole plasma is produced by one or two injecting contacts. In magnetodiodes, the effect of Lorentzian carrier deflection is not used directly, as in Hall-type sensors, but enhanced by (assymmetric) surface recombinations. Severlal approaches have been proposed.



(a) (b)

Fig. 3. (a) Conventional MOS-Hall device [8] and (b) complementary association of two dual-drain MOSFET sensors [11].

1. *p^+nn^+ magnetodiodes*

This famous sensor is actually a p^+nn^+ diode with a "long" and low-doped base (Fig. 4a). The lateral surfaces are in general provided, one with high recombination velocity, the other with low recombination velocity. Forward bias makes the end contacts inject electrons and holes concentrations exceeding the base doping. The resulting current-voltage characteristic I(V) is usually quadratic ($I \sim V^2$) and corresponds to the so called semiconductor regime of double injection. When a negative magnetic field is applied (in the plane of the device and perpendicular to the current), electron and holes are deflected together towards the high recombining surface, so that their numbers and, therefore, the current are reduced. In contrast, for positive magnetic field, carriers are pushed away from this surface towards the low recombining surface and then their average density and the current increase [12].

The family of I(V) characteristics corresponding to the magnetodiode effect are shown in Fig. 4b. The I(B) curve of Fig. 4c is more or less bell-type shaped, according to the carrier mobility and the injection rate: the maximum is around 0.1 T in Ge, but more distant and very flat in Si. For two identical surfaces (with low recombination rate) the curve I(B) becomes symmetrical for ± B.

The magnetodiode theory proceeds from the calculation of the two-dimensional distribution of magnetoconcentrated carriers [12]. It is deduced that the magnetic field can drastically modify the I(V) characteristics (the initial

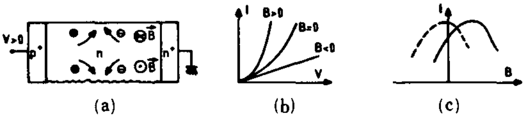


Fig. 4. Schematic representation of a p^+nn^+ magnetodiode (a) and of relevant current-voltage (b) and current-magnetic field (c) characteristics.

quadratic low becoming linear) and that other double injection regimes could be expected. An essential parameter is the magnetodiode thickness which must be of the order of the ambipolar diffusion length[13]. As this condition can not be satisfied in bulk Si, integrated magnetodiodes have been fabricated on Silicon On Sapphire (SOS) thin films[14,15]

A typical feature of SOS is that the silicon-sapphire back interface has very poor quality (high recombination rate) compared to the front Si-SiO$_2$ interface. Magnetodiodes are, therefore, the only SOS devices taking advantage of the high dissymmetry between interfaces which is usually referred to as a principal drawback of the SOS technology.

Sensitivities of 5-10 V/T or 10-150 mA/T have been obtained according to the diode length (10-50 μm, to exceed the diffusion length) and the film thickness (0.6-7 μm)[14,15].

This performance is much better than that of Hall devices, but at least an order of magnitude lower than for Ge magnetodiodes. Noise [16]. and low temperature operation [15] have been also investigated.

2. *p^+n magnetodiodes*

This device differs from the p+nn+ magnetodiode by the absence of the injecting n^+n contact, replaced by an ohmic contact. The operation of p^+n diodes is governed by the carrier longitudinal diffusion which leads to an exponential I(V) characteristc with high ideality coefficient [17]. The carrier magnetoconcentration induces a modification of the ideality coefficient [12], but the sensitivity is lower than for p^+nn^+ devices [18].

3. *Schottky magnetodiodes*

The Schottky magnetodiode is a three terminal device formed by the superposition of a small area metal-semiconductor contact on the n-base of the p^+nn^+ diode (Fig. 5a) [19]. The p^+nn^+ diode is forward biased while the Schotky diode is reverse biased. As the reverse current of a Schottky diode strongly depends on the carrier concentration under the Schottky contact, the basic operation mechanism consists in a variation of the carrier surface concentration by magnetoconcentration effect [15]. Schottky magnetodiodes, being governed by the *surface* density modulation, are expected to be more sensitive than p^+nn^+ sensors (depending on the modification of the carrier *average* density). An experimental confirmation was obtained in SOS (Figs. 5b and 5c), where Schottky sensors exhibit sensitivities as large as 30 V/T [15,19].

4. *Field effect magnetodiodes*

This device looks like a MOS transistor, except the fact that source and drain regions are respectively p^+ and n^+ doped in order to form a longitudinal gate-controlled p^+nn^+ magnetodiode (Fig. 6a). The role of the gate is to optimise, by field effect, the current path which will be thereafter modified by the carrier magnetoconcentration. Due to the double injection of electrons and holes, there are, along the channel, successive zones of majority carrier accumulation, depletion and minority carrier inversion. The sensitivity can be measured in terms of current, drain voltage or gate voltage variations. In bulk Si, the mismatch between wafer thickness and ambipolar diffusion length inhibits a strong magnetodiode effect and the performance is limited (as being due to the geometrical deflection of current lines only, not to assymmetric recombinations). In this respect, MOS-p^+nn^+ magnetodiodes have been fabricated on SOS [20].

5. *Other magnetodiodes*

Devices with original features have been obtained by modifying either the basic geometry of the p^+nn^+ magnetodiode or its operation conditions. In *filamentary* magnetodiodes the current flow is spatially localised

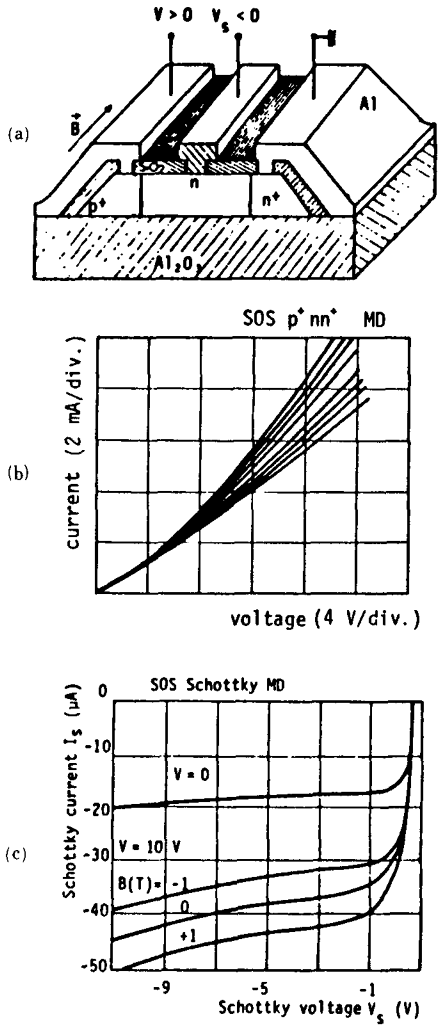
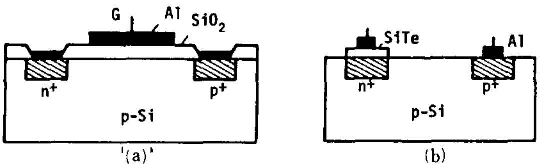


Fig. 5. (a) Schottky magnetodiode integrated on SOS and I(V) characteristics of both longitudinal p^+nn^+ (b) and Schottky (c) magnetodiodes [15]



(a) (b)

Fig. 6. (a) MOS field effect magnetodiode [20] and (b) memory magnetodiode [23]

in a narrow path. The formation of current filaments is related to entropy conservation in devices with negative resistance as *madistors* (Fig. 7a). The magnetic field makes the filament path be longer, increasing the apparent resistance of the device (Fig. 7b). Current extinction can occur if the filament reaches the sample surface. Madistors were fabricated in Ge and InSb and operated at low temperature [21]. Filamentary characteristics were also obtained in low-doped SOS magnetodiodes at high injection level [15] as well as in planar Si magnetodiodes at 77 K, the sensitivity being of 100 V/T [22].

A *memory* p^+nn^+ magnetodiode has been fabricated by inserting a thin SiTe insulating layer between the Al contact and the n^+ terminal (Fig. 6b). This layer induces I(V) characteristics with either "low" or "high" conductance, which are thereafter subject to usual magnetodiode effect modifications. The device conserves the type of conduction until its memory is erased by applying a strong current pulse [23].

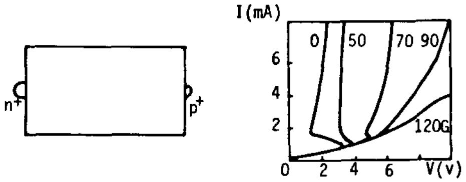


Fig. 7. Madistor (or filamentary magnetodiode) and relevant characteristics [21]

It has been already mentionned that bulk Si is not, a priori, convenient for magnetodiode integration due to the excessive wafer thickness compared to the diffusion length. To alleviate this problem a very elegant solution using CMOS process has been recently proposed [24]. A thin active base is isolated from the n-type substrate by forming a reverse biased p-well (Fig. 8a). At low voltage, this sensor operates as a p^+nn^+ magnetodiode because the well junction behaves as a high recombination interface, collecting minority carriers. At high longitudinal voltage, a part of the well junction becomes forward biased and parasitical carrier injection occurs, causing the emergence of a negative resistance region (Fig. 8b). The sensitivity of this device is about 25 V/T at 10 mA current [24].

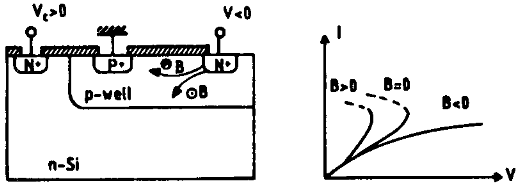


Fig. 8. Schematic representation of the CMOS magnetodiode and characteristics [24]

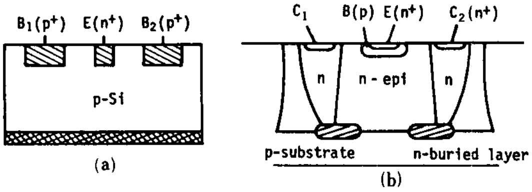


Fig. 9. (a) Double-base magnetotransistor [25] and (b) double-collectro magnetotransistor (with majority carrier deflection) [26] integrated on Si.

V. Magnetotransistors

1. *Split-terminal magnetotransistors*

These devices are symmetrical structures, half of which being designed as a classical vertical or lateral bipolar transistor. The sensitivity arises from the difference (induced by the magnetic field) between current flows received by the symmetrical teminals.

The simplest device is the *double-base* magnetotransistor (Fig. 9a), formed by two symmetric p^+nn^+ magnetodiodes. The current injected from the emitter is split into two parts, one flowing towards the right hand base and the other towards the left hand base. These two current components are submitted to opposite Lorentz forces and result in a geometrical assymmetry: one path is shortened while the other is lengthened. A gain in sensitivity (30 V/T) is obtained after degradation of the back surface (by means of proton irradiation), since the longer current lines are now also affected by the carrier recombination [25].

The *double-collector* magnetotransistor (Fib. 9b) is composed of two symmetrical and vertical npn bipolar transistors. The electrons injected from the emitter move through the base and the low-doped collector until they reach the two buried collector contacts. The role of the magnetic field is, once more, to differentiate the geometry of the two current lines. This device exhibits good linearity but moderate sensitivity ($S'_1 = \Delta I/I\Delta B = 3\times10^{-2}$ T^{-1}) [26]. A four-collector version was proposed in view of the measurement of the two horizontal components of the magnetic field [27]. Another two-collector magnetotransistor was fabricated with a lateral bipolar configuration [28].

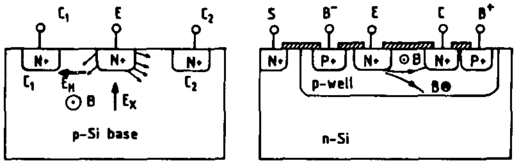
Other devices were specially designed to allow the carrier deflection in a very large base region. The difference with the previous case comes from the fact that, here, *minority* carriers are submitted to Lorentzian deflection and ambipolar effects occur. In the *dual-collector* transistor of Fig. 10a, minority carriers *diffuse* laterally towards the collectors $C_{1,2}$ whereas the majority carriers *drift* along the vertical axes (towards the emitter) to supply carriers for recombination. The relevant vertical electric field and the transverse magnetic field generate a lateral Hall field which enhances the minority carrier collection by C_2 at the expense of C_1 [29]. This modulation of the base transport factor results in a collector current imbalance. The lateral Hall field behaves at the emitter junction also, producing an assymmetric emitter-base bias and, therefore, an assymmetric electron injection towards C_1 and C_2, which increases the sensitivity (0.1 V/T) [30]. At high injection level the magnetoconcentration effect (opposite near C_1 and C_2) amplifies the collector current imbalance.

A different kind of sensor based on injection modulation is formed by the combination of two bipolar transistors with a Hall plate which represents their common base [31]. The Hall plate is biased by usual ohmic contacts and the two emitters play the role of lateral Hall probes as in Fig. 1a. The Hall voltage induced (by a *normal* magnetic field) between emitters is naturally converted into a difference in injection levels, i.e. in collector currents.

2. *Lateral CMOS magnetotransistors*

This assymmetric device is located in a p-well representing the base region (Fig. 10b). Two base contacts are used and biased to accelerate the emitter injected carriers towards the collector. Some electrons are, however, collected by the reverse biased well junction and form the substrate current. A transverse magnetic field deflects the path of electrons and modifies the number of carriers reaching the collector[32].

Another magnetosensitive effect has been observed in a standard enhanced-mode MOS transistor, operated at 77 K[33]. The only exotic condition was the forward biasing of the source-substrate juction. The sensitivity (about 1 V/T) was attributed to a pure magnetoresistance effect.



(a) (b)

Fig. 10. (a) Double-collector magnetotransistor (with minority carrier deflection) [29] and (b) lateral CMOS magnetotransistor [32].

3. *Unijunction magnetotransistor*

Commercially available unijunction transistors show very interesting magnetosensitive capability[34]. When constant bias is applied between the end ohmic contacts, the emitter current is negligible until the emitter voltage is increased to forward bias the junction (Fig. 11a). Thereafter, injection of electrons into the bottom part of the base reduces the potential value near the emitter and initiates a negative resistance process. When a magnetic induction is applied, the resulting Hall field superposes on the internal field of the junction and, according to its direction, the negative resistance region is accentuated, reduced or even suppressed (Fig. 11b). This device, biased for operation close to the critical turn-on point, detects alternative fields with excellent sensitivity (3000 V/T) and selectivity. On the other hand, the insertion of this sensor into an oscillating circuit was used for magnetic field to frequency conversion (5 kHz/T)[34].

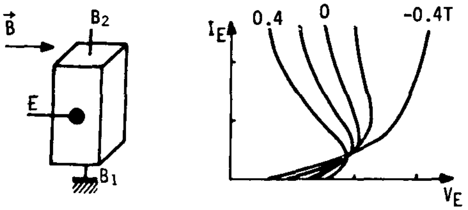


Fig. 11. Schematic view of an unijunction transistor and characteristics [34]

4. *Carrier domain sensors*

The very interesting sensor shown in Fig. 12a is a lateral bipolar transistor with circular geometry and surrounded by four sensing contacts[35]. The device is operated in the collector-emitter breakdwon regime which enables the formation of current filaments (domains). A magnetic field, perpendicular to the plane, produces, via Lorentz force, a domain rotation which is detected from the voltage pulses appearing at the sensing contacts when the filament passes by. The sensitivity of detection is 250 kHz/T for a 500 μm diameter device[35]. A similar carrier domain magnetometer has been achieved using a four layer thyristor-like structure. The device is linear, sensitive (100 kHz/T) but requires a threshold field ($B > 0.2$ T)[36].

A vertical planar magnetothyristor is illustrated in Fig. 12b. The magnetic deflection of the current path results in a modification of the turn-one voltage. The sensitivity can be increased to 100 V/T by superposing the field effect induced by a gate deposited on the wafer back surface[37]. Finally, a vertical dual-collector thyristor was recently proposed and shown to exhibit good sensitivity (3 mA/A) [38].

VI. Conclusion

The aim of this review was to point out how diverse and interesting is the magnetic sensor family. To created new devices a lot of ingenuity is necessary for the combination of original

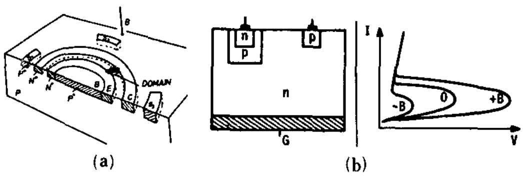


Fig. 12. (a) Configuration of the carrier domain magnetometer with transistor-like circular geometry [35] and (b) gate-controlled vertical magneto-thyristor [37]

physical principles with relevant technological possibilities. It is expected that a tremendeous development of sensors, in general, will take place in the next years, giving rise to yet more exciting research. And what is more attractive than the magnetic field?

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用語解說

MUMPS

언어 프로세서, 제어 프로그램, 데이타 베이스가 일체가 된 특수한 오퍼레이션 시스템

Operating Freguency

어떤 탐촉자에서 동작하는 최적의 주파수.

거리 분해능

음파의 전파 방향에서 반사체의 거리를 분리시킬 수 있는 최소의 거리

게이팅 (Gating)

탐촉자가 펄스를 발생시킨 후, 어떤 특정 시간에 도착하는 반사파만을 통과시키는 것

근거리 음장 (Near field)

탐촉자로부터의 거리가 멀어짐에 따라 음파의 음속 직경이 감소하는 영역.

다이나믹 레인지 (Dynamic range)

시스템이 처리할 수 있는 최대와 최소 출력의 비,

'86년도 신규회원 소속별 분류

삼성반도체통신(연)	39명	국방과학(연)	4명	인하대학교	1명
한양대학교	10명	서울대학교	3명	아즈대학교	1명
고려대학교	9명	대전기계창	3명	건국대학교	1명
경북대학교	8명	금성통신(연)	3명	한국전자통신(연)	1명
국방대학원	5명	성균관대학교	3명	한국과학기술대	1명
과학기술원	4명	동국대학교	2명	한국전기통신공사	1명
중앙대학교	4명	연세대학교	1명	기타	42명
				계	148명