

Table 1 OPTICAL POWER MEASUREMENTS AND COUPLER PARAMETERS

Type	Taper ratio R	Taper length	Fibre output power	Efficiency	Improvement ratio
Fig. 1a	4.1	cm 4.7	mW 0.52	% 87	2.9
Fig. 1b	3.5	0.43	0.58	97	3.2
Butt joint			0.18	30	1
Spherical end			37	61	2.1

acceptance angle for light at the input end of the unclad taper is 90° when the refractive index of the core n_c is larger than $\sqrt{2}$. Using this assumption, and neglecting Fresnel reflection losses and the separation between the taper end and the light source, all the light radiated from a source which is smaller than the end of the taper can be trapped in the taper. The taper then gradually directs this trapped light to propagation angles which correspond to guided modes in the optical fibre in the following way.

In a structure as shown in Fig. 1a, the repeated reflections of the ray in the tapered section causes the propagation angle between the local wave vector of the ray⁷ and the axis of the taper, θ , to reduce as

$$\sin \theta_2 = \sin \theta_1 \left(\frac{u_2}{u_1} \right) 1/R \quad (1)$$

where $R = a_2/a_1$, the subscripts 1 and 2 refer, respectively, to the input and output ends of the tapered section and u is the transverse component of the local wave vector multiplied by the local core radius. This equation states the conservation of the magnitude of the local wave vector through the taper.⁷ For long tapers, such as we use here, u_2/u_1 is approximately unity,⁸ and thus the action of taper is to increase the numerical aperture of the fibre to a value

$$(n.a.)_{eff} = R n_c \sin \theta_c = R(n.a.)_0$$

where $\theta_c = \sin^{-1} \{(n.a.)_0/n_c\}$ is the critical angle of the clad fibre and $(n.a.)_0$ is its numerical aperture.

The degree of improvement in coupling efficiency that the taper provides over that of a simple butt joint then depends on the emission pattern of the source. A Lambertian emitter is coupled to a fibre with an efficiency⁹ proportional to $(n.a.)^2$ and thus the improvement in coupling efficiency is given by R^2 , the maximum allowable by the Liouville theorem⁹ for a Lambertian source if we consider that the source has the same area as the taper end. The emission pattern from a d.h. laser diode usually spreads wider than the acceptance angle of a fibre only in the plane perpendicular to the junction plane, and this was the case for the diode we used here. We would therefore expect the taper to improve

coupling over that of a simple butt joint by a factor of R , rather than R^2 . The ratios shown in Table 1 are consistent with this expectation. Maximum coupling is obtained merely by ensuring that the taper ratio R is large enough to raise the value of efficiency of butt-joint coupling to one.

In summary, we have shown that use of a taper coupler provides a means of efficiently coupling between a d.h. laser diode and a multimode fibre. The technique is simple and the results easily reproducible. We conclude that the tapered end is one of the most promising power-coupling techniques.

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NOVEL MAGNETIC-FIELD SENSOR USING CARRIER-DOMAIN ROTATION: PROPOSED DEVICE DESIGN

Indexing terms: Bipolar transistors, Magnetic-field measurement, Semiconductor devices, Transducers

A bipolar semiconductor device is described in which a mobile domain of current rotates around a circular path at a rate proportional to a magnetic field, when this is perpendicular to the planar structure, or follows the magnetic vector when this is in the same plane. Potentially high sensitivities are possible, since the response is inherently integrating; practical limitations to this are discussed.

Introduction: It is noteworthy that most solid-state magnetic sensors utilise a principle known for almost a hundred years—the Hall effect¹—in which the deflection of majority carriers in a thin conducting plate produces a transverse electric field in the presence of a perpendicular magnetic field. The resulting output voltage is usually only millivolts, and is often accompanied by components arising from other galvanomagnetic and thermomagnetic effects, and is prone to errors due to contact misalignment. Hudson has described²

a novel sensor in which current in the base region of a lateral $p-n-p$ transistor can be deflected to one of two collector diffusions, producing a differential current output from a high-impedance source. However, to date all semiconductor sensors have been of the equilibrium type, that is, some restoring force arises to prevent further deflection of carriers.

The device described here has inherently high sensitivity because deflected carriers do not generate a restoring force, but are allowed to move freely around a closed path, usually at the circumference of a circular structure. The device has the further unique property of generating an output in a digital form (revolutions per second), which in many applications is highly advantageous, particularly since the frequency typically falls in the range 1-100 kHz. The direction of rotation follows the sense of the applied field, which is readily conveyed as part of the output signal by the use of three or more output taps around the circumference. An alternative application of the device is in tracking the direction of a magnetic vector applied in the plane of the structure, which may prove useful as a remote-sensing compass transducer of

very small mass and volume, producing synchro-like analogue output signals.

Background: The concept of a carrier domain was introduced by the author³ in 1971, and can be exploited with devices fabricated using standard bipolar technology. Minority-carrier injection from an elongated emitter is restricted to a small zone by means of bias voltages applied to the base diffusion. Both the position and the magnitude of the domain can be accurately controlled, and several useful functions can thus be performed, notably analogue multiplication, an early design being given in Reference 4. Smith has described an improved carrier-domain multiplier.⁵ In these structures the domain was relatively diffuse (roughly Gaussian in shape and about 15% of the emitter length to the half-magnitude points). A further technique, that of domain enhancement, was conceived, by which means an initially diffuse domain can be intensified by a spatial positive feedback mechanism, the conditions for which can be produced in a $p-n-p-n$ structure.

Clearly, a narrow domain of current flow ought to behave like the textbook 'elemental conductor' in a magnetic field, and to test this hypothesis various linear and circular structures have been built, some providing analogue readout of domain position by the use of resistive diffusions which act both as lateral $p-n-p$ collectors and the means to resolve the centre of the domain, while others use discrete collectors to provide some indication of domain geometry by deconvolution. This letter describes the original design for a circular magnetically responsive device in which readout of domain angle was sensed by a resistive collector ring contacted at four points spaced by 90°. Although this device was built, domain rotation was not satisfactorily confirmed and the results were consequently not published. Recently, devices having essentially the same geometry have been fabricated and successfully operated at Southampton University. This letter is confined to a description of the original design and an analysis of the rotation mechanism; detailed results are presented in a complementary letter.⁶

Device construction: The essential parts of the sensor are shown in Fig. 1, which is not to scale. All the regions are circular and formed by standard diffusion techniques. An n -type epitaxial layer, of approximately 1 Ωcm resistivity and 5 μm thick, forms both the collector of a planar $n-p-n$ transistor and the base of a lateral $p-n-p$ transistor, and is bounded by the usual isolation diffusion (not shown), approximately 500 μm in diameter. An ohmic connection is made to the centre of the epi disc. Boron diffusions form (a) a disc which acts both as the base of the $n-p-n$ transistor and the inner collector of the lateral $p-n-p$ transistor, contacted by a metallisation ring near its centre, (b) an inner annulus which is contacted along its length and forms the emitter of the $p-n-p$ transistor and (c) an outer annulus contacted at four points, acting simultaneously as a second collector for the $p-n-p$ transistor and as a resistive current divider. A ring of n^+ buried layer was placed under the active region of the lateral $p-n-p$, the purpose of which was to maintain a high ratio of lateral to vertical current transport. Finally, a phosphorus n^+ diffusion forms the emitter ring of the $n-p-n$ transistor, also contacted along its length.

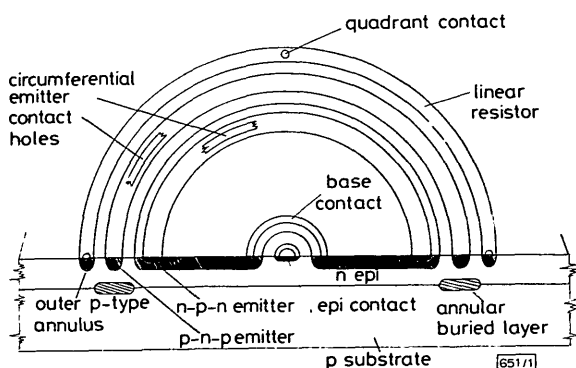


Fig. 1 Plan/section view of the magnetic sensor

There are ten bonding pads (not shown), including four for angle readout and two to each emitter

Operating conditions: Both emitters are current driven from external supplies of roughly equal magnitude in the range 1–10 mA, and all collector junctions are reversed biased by a few volts. Practically all of the $n-p-n$ emitter current flows in the epi disc to the centre contact. Roughly half the $p-n-p$ emitter current flows inward to the base disc (the other half flows outward to the resistive annulus) and this current flows under the high-resistivity sheet below the n^+ emitter before arriving at the central base contact. A perfectly symmetrical device would exhibit uniform injection under these bias conditions, but the system is inherently unstable and any small imbalance (thermal gradient, thermal noise, diffusion inhomogeneity etc.) causes regenerative bunching of injection, resulting in an enhanced domain at a random point on the circumference where practically all minority-carrier injection is concentrated. Most of the emitter areas are forced into reverse bias.

It is useful to have an equivalent circuit of the device; Fig. 2a shows two 10° sections. Of course, the structure is not so simply modelled, the actual 2-dimensional current-density and potential distributions being determined only with great tediousness, but it does reveal the $p-n-p-n$ connection, and can be used to simulate the regenerative process.

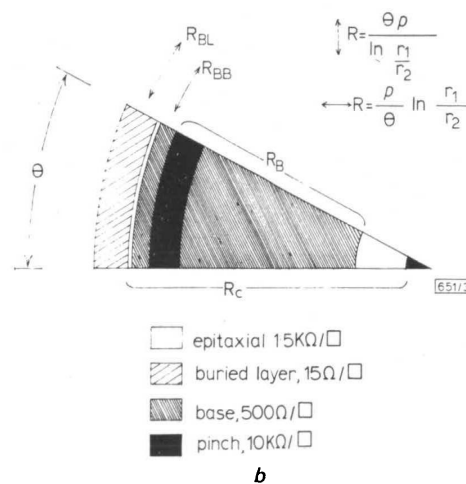
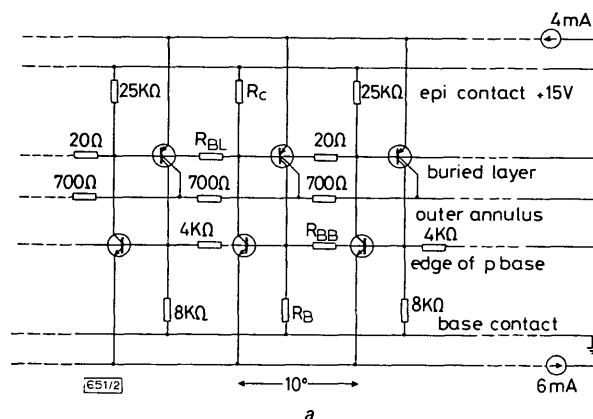


Fig. 2

a Lumped equivalent circuit. The complete device consists of 36 sections in a ring
b Sector for calculation of equivalent resistances. Note that R_B consists of two radial sections in series, and R_C is actually epitaxial material

The resistance values were determined using the sector shown in Fig. 2b, and a notable feature of the model is the very low value of R_{BL} . It is now believed that this was the reason for the failure of the original design, since injection from the $p-n-p$ emitter is not strongly modified by $n-p-n$ collector current, and the domain would consequently be very diffuse. A better design compromise would have been to have omitted the buried layer and to have tolerated the large loss of carriers to the substrate.

Magnetic response: When the biased device is placed in a magnetic field B all carriers (majority or minority, within the domain or in the resistive sheets) are subject to Lorentz forces $q(V \times B)$, where V is the appropriate carrier-velocity vector, and it is readily shown that this results in a net clockwise rotation of the domain when the field is into the plane of the semiconductor. A simplified explanation of device

behaviour can be given by considering just the inward flow of current across the base region of the lateral $p-n-p$ transistor, the mean radius of which is R . Holes injected from a given point on the emitter undergo deflection and arrive with some circumferential displacement at the edge of the p -type disc, raising the potential of the $n-p-n$ base (which this also forms) at the displaced point and thus shifting the centre of the electron domain under the n -type emitter. In turn, this causes the potential minimum in the epi sheet ($p-n-p$ base) to shift, resulting in the original centre of the hole domain to be moved by a small distance d . For fields of practical interest, d will be proportional to the field strength. The time taken for a shift of this amount is the summation of several delays, the dominant being that due to hole transport across the $p-n-p$ base, $1/\omega_T$. From this, the time required for one complete revolution can be readily calculated. Expressed as a rotational frequency

$$f_r = \frac{K f_T B}{R}$$

where B is the magnetic field perpendicular to the plane of the semiconductor and the constant of proportionality K is primarily a function of the Hall mobilities and the radial distance between the centroids of the hole and electron domains.

It would appear that the primary criterion for successful operation of sensors based on this principle is that some degree of bunching of carriers is needed, to provide sensing of the rotation of carriers. Indeed, even a slight imbalance of carriers to one side of the device would be adequate. This suggests several new device structures in which there is no true domain formation.

Minimum field for rotation: Ideally, the device would have perfect circular symmetry and, for very weak fields, the domain would drift around the circumference. In fact, a certain critical field will always be required to overcome the solid-state equivalent of stiction, which can be expected to arise from several kinds of inhomogeneity, including (a) variation in diffusion depths across the plane of the structure, (b) variation in doping concentrations, (c) thermal gradients, (d) mechanical stresses induced by die attach and wire-

bonding, (e) subsequent strain caused by package deformation under conditions of use, (f) residual magnetisation of materials used in packaging, (g) mask misalignment and (h) random defects of various kinds.

Voltage drops in the emitter metals are also troublesome, since they have to be narrow and long, and the currents are high. A further interesting source of asymmetry is that due to the nonperpendicularity of the field; the radial component will cause the domain to tend to line up with it, rather than move in response to the perpendicular component. However, there is clearly a critical angle at which this effect will be seen, and it is unlikely to be as significant a cause of stiction as the above effects.

The transfer curve relating B to f_r will show a step discontinuity, with linear regions which extrapolate back through the origin. The stiction problem may be overcome by the use of an alternating bias field. The net rotation would be nulled for zero d.c. field by balancing positive and negative halfcycles of the a.c. field.

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NOVEL MAGNETIC-FIELD SENSOR USING CARRIER-DOMAIN ROTATION: OPERATION AND PRACTICAL PERFORMANCE

Indexing terms: Bipolar transistors, Magnetic-field measurement, Semiconductor devices, Transducers

A magnetic field applied to a circular $p-n-p-n$ structure causes rotation of a carrier domain, the localised region where bipolar-transistor action occurs. A theoretical explanation is given of device operation, including the dependence of rotation frequency on flux density. Experimental results are given for a prototype device.

Introduction: A carrier-domain device (c.d.d.) first proposed by Gilbert¹ consists of an extended bipolar-transistor structure within which current flow is restricted by means of controlled emitter crowding to one localised region, known as a domain. The first such device was described by Gilbert,¹ and he has since proposed a carrier-domain magnetic field sensor in which the domain should rotate at a rate proportional to the field. Fabrication and successful operation of such a device is reported here.

Device description: In a companion letter, Gilbert² describes the structure of the carrier domain magnetic-field sensor and explains the formation of a self-sustaining domain by means of positive feedback between the annular $p-n-p$ and $n-p-n$ transistors. Fig. 1 is a photomicrograph of such a device designed and fabricated at Southampton University. This differs from the structure described by Gilbert in that it has twelve subsidiary $p-n-p$ collectors in order to sense the position of the domain, and has no buried layer diffusion beneath the lateral $p-n-p$ transistor base.

The device has a diameter of 600 μm and was fabricated on a 2 Ωcm n -type substrate. The boron p -type diffusion has a sheet

resistivity of 120 $\Omega/\square$ and the phosphorus n -type diffusion a sheet resistivity of 4 $\Omega/\square$.

Magnetic sensitivity: The following explanation is put forward for the effect of a normal magnetic field on the device. It can be shown that the magnetic field distorts the potential

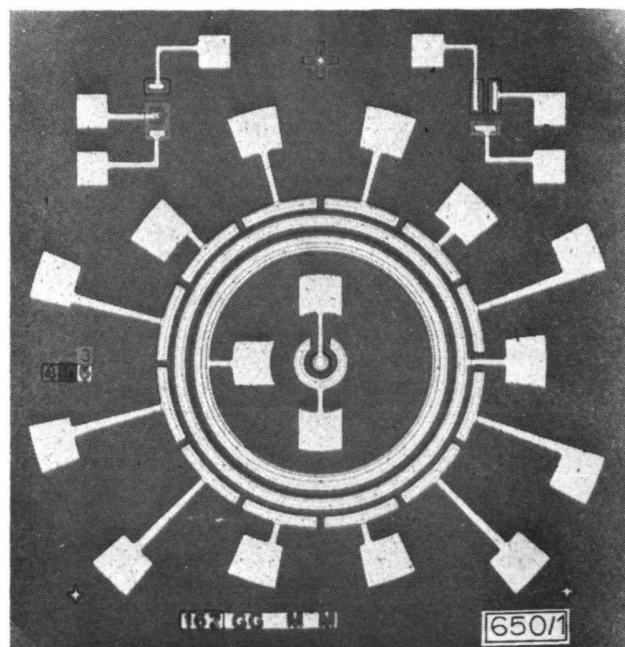


Fig. 1 Photomicrograph of prototype magnetic-field sensor
Diameter 600 μm