FORTY YEARS OF TECHNOLOGY IN MICROWAVE RECEIVERS AT THE GEC HIRST RESEARCH CENTRE - A BRIEF HISTORICAL REVIEW 1940'S TO 1980'S

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A brief review is provided of some of the GEC Hirst Research Centre technology advances for application in microwave heterodyne receiver developments during the 1940's to 1980's, through the phases of the waveguide/coaxial point-contact device, the planar device/circuit for the MIC (Microwave Integrated Circuit) and the early MMIC (Monolithic Microwave Integrated Circuit).

1. Introduction

The GEC Research Laboratories, later GEC Hirst Research Centre (HRC), was first founded in 1919 with the aim to pursue research independently of product manufacture, the purpose built laboratories at Wembley was opened in 1922 [1]. It was closed in the 1990's. This paper is a tribute to HRC and its scientific technologists, as it traces just some of the many advances made in microwave receiver technology over four decades.

Fig. 1. The GEC Hirst Research Centre 1960's

2. 1940's Background

In 1938 the GEC applied its Laboratories commercial expertise to help the war effort. One example of this was in radar development by using its extensive thermionic valve experience to transmitting and receiving applications, for both radar and communication military needs. Work on glass magnetrons had started as early as 1931, but in 1940, based on the work by Randall and Boot at Birmingham University, the Laboratories applied its capability to further the realisation of the cavity magnetron to practical microwave devices, by the development of the 3 GHz E1189 high power magnetron. HRC also developed glass thermionic-valves for receiver application, the last of these for the British 50cm ground radar equipment, before studies showed the superiority of the semiconductor crystal diode as centimetric radar became practical; and the crystal mixer became adopted for frequencies above about 500 MHz. A tungsten wire in contact with a silicon chip as the rectifying element was favoured and this was mounted in a range of capsule outlines in the early stages of development, for application in coaxial and waveguide equipment, leading ultimately to a preferred cartridge

encapsulation. An in depth discussion of device technology of this early era is provided by Torrey and Whitmer [2]. The general 1940's practice in radar equipment was to tune each crystal mixer individually by the use of variable tuneable mounts, but later the fixed tuned mount came into use, which implied repeatable control of the mixer diode characteristics. To meet these requirements and to provide better shielding properties from stray radiation, the UK favoured a coaxial encapsulation in place of the cartridge, and in the late 1940's the GEC Laboratories together with BTH (later AEI Semiconductors Ltd) became involved in the development of a coaxial construction, to meet both 3 GHz and 10 GHz (S and X-band) applications; opposite polarity devices being required for balanced mixer designs; the USA continued with development of the cartridge outline, with a removable end-cap for reversing polarity, for these frequencies.

3. The 1950's

During the 1950's, R&D (Research and Development) at HRC was applied to the 1940's Si (silicon) point contact diode basis to ensure a production status for frequencies up to 40GHz. In the latter part of the year studies were initiated into the Ge (germanium) point-contact diode.

The main development emphasis was placed on the UK X-Band coaxial diode, shown in Fig.2; the rectifying contact was formed by a tungsten wire in pressure contact with a bulk p-type Si chip (carrier concentration $n \sim 10^{18}$ cm^{-3} cc**)**; the junction being formed using a mechanical vibration technique (commonly known as "tapping"). The prime receiver requirement was sensitivity (ability to detect a low signal) specified by the ONF (Overall Noise Figure) [2,3], at a stated i.f. (intermediate frequency) and Fif (i.f. amplifier noise figure). The requirement of fixed tuned mounts and balanced mixers, however, also implied a very demanding tight r.f. (radio frequency) admittance window specification, imposing very tight control of rectifying junction properties and mechanical constructional/dielectric parts [3]; for example, by an r.f. admittance window at X-Band specified as 1.43 max. v.s.w.r. (voltage standing wave ratio) centred at 0.8 + 0.2j with respect to a 1/68 mhos coaxial line. The ONF for these devices was typically 9.0dB (2dB Fif at 45MHz), The devices were produced in numbers of about 5000 per year during the peak demand (shared between GEC and BTH), and were still being produced albeit in lower numbers up to at least the late 1980's. The large production numbers were a reflection of radar system problems with t.r. cell spike leakage burnout, as many equipment's changed the diode routinely after a specified operation time. The mechanism of t.r. cell burnout was extremely complex, the effect could be catastrophic, occur with time at an energy level below catastrophic, or be a recoverable temporary deterioration in sensitivity during the transmit pulse. Many studies were carried out in the 1950/1960's to improve the burnout performance, but it was not until later with the application of solid-state devices e.g. varactor limiters in conjunction with t.r. cells, pin switch /limiter combinations, pin switches, etc., that considerable improvement in receiver burnout performance was made.

The Si point-contact technology was later also employed for mixer diode development to meet radar requirements at about 35 GHz (Q-Band). The UK plug-in WG (waveguide) device structure, shown in Fig.2, developed at HRC (and BTH), positioned the rectifying contact across the waveguide (WG22), the ONF was typically 13dB (Fif=2dB at 45MHz); the USA, however, preferred coaxial constructions for frequencies between 12 and 40GHz.

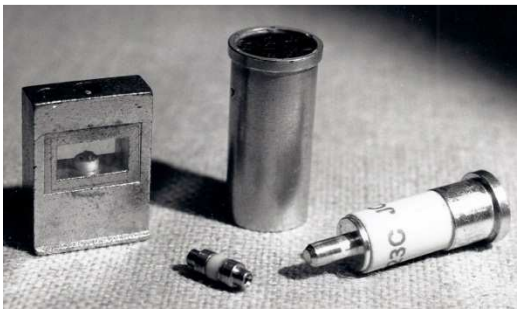

Fig. 2.1950's/60's Crystal Mixer Outlines
From left: UK Q-Band Plug-in WG; Double-Ended Capsule; S/X-Bands coaxial;
S/X-Bands Cartridge

The well-known theory of mixers predicted the desirability of a high mobility semiconductor material for low Lc (Conversion Loss) and in the late 1950's research was undertaken at HRC into both Ge and GaAs (gallium arsenide) point contact diodes. These studies resulted in retrofit devices to the Si at 9.5 and 35 GHz, using a titanium wire with a pulse formed point-contact junction on a bulk n-type Ge chip ($n \sim 10^{18}$ cm^{-3} cc) [3]. The Ge diode development resulted in ONF's at 9.5 and 35 GHz of typically 8.0dB and 11.0dB (2dB i.f. at 45MHz), i.e. an improvement in ONF of approx. 1db and 3dB compared with Si at 9.5 and 35GHz respectively.

4. The 1960's

By the end of the 1950's, Si point-contact devices (both coaxial and WG) had been developed to a production status and together with all relevant activities transferred to a GEC Product Group. During the 1960's, although the main studies concentrated on advancing the Ge point-contact device technology, others included for example: novel point-contact diode encapsulations; the Ge backward (tunnel) diode; and the initiation of studies into the GaAs Schottky Barrier diode together with hybrid MIC's (microwave integrated circuits), thus providing the MIC technology base for system exploitation in the 1970's.

Interest was expressed in the early 1960's in using the characteristics of the tunnel diode as a rectifying element at microwave frequencies. Both n-type GaAs and Ge backward (low peak current tunnel) diodes were studied at HRC, with the conclusion that Ge was the more acceptable semiconductor material. The problem of producing an appropriate low capacitance junction for microwave operation was resolved at HRC by the development of a junction forming technique which employed a gallium (p-type dopant) plated gold whisker wire, pulse bonded to a highly doped n-type Ge chip [4]. Devices were developed in the standard Si-point contact outlines, which found microwave application as a zero bias, high sensitivity detector, i.e. -56dBm tangential sensitivity (1MHz video bandwidth) compared with -52dBm for a metal semiconductor device with fwd bias. The device showed useful mixer properties of low l.o. drive (for receivers with limited l.o. power), e.g. 8.0dB ONF (Fif=2dB at 45MHz) at X-band with ~100µW l.o. drive, and low flicker noise for Doppler radars with a noise corner of about with 100kHz i.f. (i.e 16dB ONF with 3kHz i.f.), however, the associated low dynamic range upper limit and poor burnout characteristics were a limitation for many applications.

Development progress in the Ge point-contact device in the early 1960's, introduced a new, unique to HRC, miniature all brazed double-ended capsule (length ~6.5mm), shown in Fig.2. The objective was to overcome the frequency limitations of the existing encapsulations and provide a versatile common package (reversible for balanced mixers) to cover all bands up to the millimetre-wave range [5], with application in WG, coaxial and stripline equipment. The devices offered typical ONF's of 6.0 and 8.5 dB (Fif = 2dB at 45MHz) at 9.5 and 35 GHz respectively, with application up to 140 GHz [6]; believed to be a world leading performance at that time. Studies at X-Band into the effect of image frequency termination when used in conjunction with a narrow band high Q t.r. cell, stressed the importance of adjusting the distance between the t.r. cell and the mixer terminals to optimise the image termination, for best receiver performance [7].

In 1965, however, the Ge technology was overtaken by the event of the Schottky Barrier diode, and further exploitation of point-contact devices was phased out at HRC with all technology being transferred to a GEC Product Group. R&D emphasis at HRC was redirected to planar technologies to study the potential of epitaxial n-type GaAs Schottky barrier diodes and microwave integrated circuits. GaAs was preferred to the more established Si material for the diode studies, due to its higher electron mobility and HRC in-house epitaxial GaAs capabilities; the device represented a breakthrough in mixer diode technology and offered many distinct advantages over the point-contact in both performance and fabrication [8]. Initially the diode chips were mounted in the LID (leadless Inverted Device) ceramic carriers, before adaptation into standard microwave coaxial outlines (a preferred technique to the multi-dot whisker contact option) for immediate application in existing equipment and comparative microwave assessment compared with point-contact technology. Early devices exhibited ONF's of ~6.0dB at 9.5GHz and ~10dB at 94 GHz, later the 94GHz performance improved to ~8.0dB; the dynamic range indicated a significant advantage over the point-contact, i.e. approx. -20dBm to ~0dBm 1dB compression point. T.r. cell spike burnout indicated little improvement, thus studies were undertaken by HRC into barrier contact metallization systems with the result that levels of >0.5 e/s could be achieved (compared with approx.0.2 e/s for point-contact) [9], the technology, however, was never adopted in production due to complexity and cost, and the progress in solid-state Rx protection.

The drive to MIC's, for small, low-cost devices in volume, was met by HRC by exploring the open microstrip transmission line; in HRC opinion this offered the most versatile transmission media. Thus, following basic studies of strip transmission lines, e.g. fabrication and microwave characteristics, then circuit design and active device embedding, the studies led through the logical stages of X-Band single-ended and balanced mixer designs [10]. The first MIC balanced mixer was produced in 1966, but by 1967, development had established the design of a microstrip 9.5 GHz MIC balanced mixer component with an ONF ~ 6.0dB (Fif=1.5dB at 60MHz); the component was marketed on a commercial basis. In 1967, the above mixer circuit was incorporated in an integrated super-heterodyne receiver, which was demonstrated in a short range 10 Ghz link at the 1968 Physical Society Exhibition; believed to be a world first [11]. The unit also included, on separate ceramic substrates, a microstrip resonator varactor-tuned Gunn l.o. (local oscillator) providing 5mW output power and 300 MHz electronic tuning, a varactor diode low pass filter network power limiter providing 20dB protection up to 200 W peak (0.5µs 2000pps), together with an IC wide-band i.f. amplifier in a compartmented box; unit size 8 x 3 x 2 cms. In 1968, the receiver design was improved to overcome the noise, instability characteristics and difficulty in effecting mechanical tuning of the low Q microstrip l.o., by replacing the microstrip l.o.

with an external, but integral, pre-tested high Q coaxial cavity Gunn l.o., providing 10mW output power and 500MHz mechanical & electronic tuning. The IC i.f. amplifier was also replaced by a 45 MHz discrete device circuit. The unit ONF was typically 8.5dB [12] and is shown in Fig.3. The method of l.o. incorporation was adopted for the majority of further MIC receiver units and sub-assembly developments.

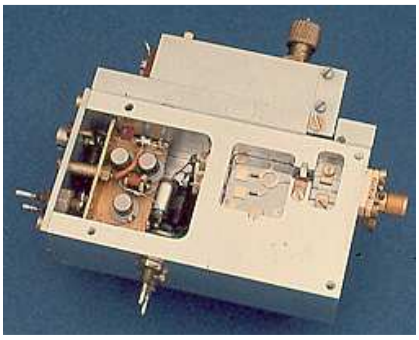

Fig.3. 1968 X-Band MIC Receiver

5. The 1970's

All the HRC point-contact/pulse bonded diode and most of the waveguide encapsulated GaAs Schottky barrier diode development activities had been phased out by the end of the 1960's, and in the 1970's, HRC concentrated on extending its research studies of hybrid microstrip MIC's, and extending the frequency range to millimetre-waves (i.e. 30 to 100GHz),.

Receiver noise figure was of prime importance in early systems and HRC renewed its interest, explored in the 1960's, in image recovery techniques, i.e. recovery of signal power normally lost to the mixer image termination, to enhance receiver performance, a concept well known in theory [2], but not really found to be a practical proposition until the advent of the MIC. The early 1970's saw considerable interest in this low-noise objective by a circuit in which two mixers are phase coupled appropriately, and HRC had a leading international involvement in these studies [13]; the results showing the desirability of compact mixers and short circuit image termination [14]. With the event, however, of advances in three-terminal device r.f. amplification, much of the work was ultimately applied to image rejection mixers, i.e. S.S.B (single sideband) receivers.

The favoured MIC packaging was a machined metal single cavity box. This form of packaging, however, could form a significant part of a component/sub-assembly overall cost, and during the 1970's, HRC undertook studies into the feasibility of plastic encapsulation using transfer moulding techniques, with the aim of reduced cost and weight. The results indicated the possibilities of the technique, as demonstrated by the fabrication of balanced mixers at 17GHz, which provided a comparable performance to the conventional build, i.e. ONF ~7.0dB (1.5dB Fi.f.at 60MHz) [15]. The studies, however, were not progressed to more complex MIC structures, as a break even cost occurred above several hundred units (i.e. in excess of requirements at that time), and the technique implied a throw away policy, when many applications required a packaging which was accessible for circuit repair.

Much of the research emphasis in the 1970's, however, was placed on the development of multi-circuit technologies embracing sub-systems, e.g. broadband video detector units (incorporating beam lead backward diodes), up and down converter units (including SSB), BITE (built-in-test-equipment) delay line modules, low noise front-ends,

transmit-receive (Tx-Rx) units etc. There were two noteworthy technologies believed to be unique to HRC, which played an essential role in these developments, namely: (i) the ferrite disk insert device for integrated non-reciprocal isolator and circulator functions, which provided a technique for embedding a ferrite disk into the substrate with a permanent magnet positioned appropriately beneath; typical performance achieved 0.5dB insertion loss, >20dB isolation for 10% bandwidth [16]; and (ii) the GaAs Schottky barrier beam lead mixer diode, in which the early 1970's progressive development in a family of devices resulted by the late 1970's in a glass insert technique for minimising all associated parasitics combined with a rugged structure, with a cut-off frequency (defined as $1/2\pi RsCjo$) of ~2500Ghz, Lc (conversion loss) 6.5dB and 7.5dB at 94 & 140 GHz respectively; still in production to-day [17, 18].

A 16.5 GHz (Ku-Band) compact low-weight Tx-Rx unit for hand-held radar applications provides a good example of multi-circuit sub-system technology [19] (principle applied later up to 100GHz). The Tx-Rx unit incorporated signal and a.f.c. (automatic frequency control) channels driven by a common l.o., with overload protection and i.f. and a.f.c. head amplifiers incorporated in the package housing. In 1971, the first experimental unit used six separate but linked sapphire substrates ($15mm^2$ x 250µm) in a package approx.6 x 8 x 3 cms; weight ~150 grams. The microstrip circuit functions included beam lead diode signal and a.f.c. rat race coupler balanced mixers, ferrite disc insert circulator, varactor diode filter network power limiter, and pcb (printed circuit board) low frequency circuitry; the pre-tested mechanical and electronically tunable coaxial cavity Gunn l.o. was externally connected. In 1972, the unit was redeveloped and later engineered to military environment specification; it was believed to be one of the most advanced MICs of its time [20]. Shown in Fig.4, the circuit functions were produced on a single alumina substrate (45 x 30mm x 500µm thick), the power limiter was a pre-encapsulated PIN device (PIN diodes with bias derived from SBD's), and the pre-tested mechanically and electronically tunable Gunn l.o., was incorporated by a separate integral coaxial cavity within the overall housing (so called partially-integrated). Essential performance included 10dB ONF, 700 MHz tuneable range, 100W peak power (duty ratio 0.001) handling at aerial input, and nominal 3W peak (duty ratio 0.001) Tx power capability. An extension of this technology is shown later in Fig.5.

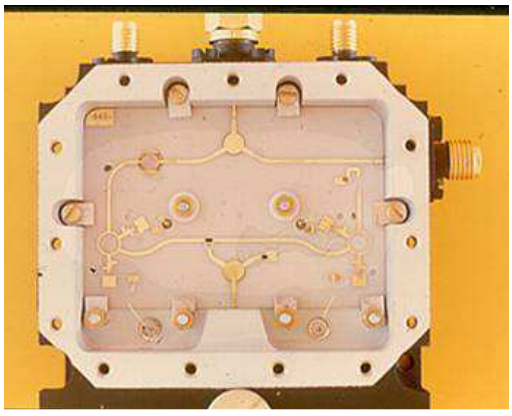

Fig. 4. 1972 Ku-Band MIC Tx-Rx Sub-System

A significant system interest in extending MIC technology up to millimetre-wave frequencies was also met in the early 1970's, when the early study phase of microstrip technology applied to frequencies up to 100 GHz was shown to be practical; the significant differences being: (i) use of a lower permittivity substrate such as fused silica (a rigid substrate being preferred to a plastic) and later Z-cut quartz (better thermal expansion

properties for ferrite insert technology and ground plane soldering); and (ii) the incorporation of waveguide to microstrip transitions, for example: tapered then multiple stepped ridge, included combining a two-step ridge within the box wall, with the option of hermetically sealing the WG aperture with a low-loss glass window; and the E-plane probe in which the circuit ground plane is removed where the microstrip line protrudes into the WG [21, 22], but later also providing the option of forming an hermetic sealed WG window [25].

By 1973, two sub-assembly demonstrators were initially produced which confirmed the feasibility of the microwave technology at millimeter-wave frequencies; (i) a 35 GHz multi-circuit integrated front-end, which incorporating signal and a.f.c. channels (mixers and head amplifiers), l.o. iso-circulator, with built-in stepped ridge WG to microstrip transition feeders; the early development included four interconnected fused silica substrates (10 x 10mm x 250 µm) with one additional ferrite substrate for the iso-circulator, later the unit included all circuits on a single Z-cut quartz substrate (35 x 25 mm x 250µm) with a ferrite insert circulator; and (ii) a 35GHz super-heterodyne receiver incorporating a bolt-on pre-tested WG cavity 2^{nd} harmonic Gunn l.o., separate linked quartz substrates containing a ferrite insert iso-circulator and a balanced mixer, both with probe transitions, and a pcb i.f. amplifier.

Following 1975, the frequency range of three terminal device r.f. amplifiers was extended into the mm-wave frequencies and attention was given to the development of SSB receiver units incorporating the appropriate r.f. circuit, ridge WG-microstrip transitions and 90^0 i.f. output combiner with thick film i.f. amplifiers, in the same package.

By 1977, component developments, based on the lower frequencies designs and technologies, had progressed up to 100 GHz. A 75 GHz (W-Band) balanced mixer was produced and marketed by HRC in 1978; it was believed to be a first commercial W-Band integrated product. By 1978, 94 GHz mixers were developed, and together with advanced ferrite insert technology, the basis was being applied to multi-circuit subsystems with both ridge and probe microstrip transitions.

By 1978, single substrate multi-circuit technology had been established and military environment standards were becoming an essential build criterion with the development of integrated sub-assemblies engineered with production in mind; such units included thick film low frequency circuitry and were hermetically sealed incorporating a pinch-off tube to provide means for back filling with an argon /helium mixture for leak testing. For example, (i) SSB Receivers for both 3 and 10 GHz: The circuits were designed for image suppression following r.f. amplification, but were essentially image recovery mixer circuits [23]. The 3 GHz unit incorporated two compact quad diode mixers and exhibited an ONF of about 5.0 dB, the circuit at 10GHz used two branch arm mixers and exhibited an ONF of about 6.0 dB (compared with approx. 7.5dB for a previous unit designed for image suppression only). (ii) A 16.5 GHz duplexer-receiver sub-system for hand-held radar systems, shown in Fig 5. Based on the unit described earlier, this version included five ferrite insert non-reciprocal devices, a 50W power PIN limiter and was designed for higher Tx power of about 50W peak, with novel power screening techniques [24], and (iii) A 94 GHZ integrated subsystem, shown in Fig. 6. This comprised a SSB modulator used as an up-converter, in which both upper and lower sidebands are accessed separately and used as l.o. feeds for two balanced mixers. The microstrip circuits on Z-cut quartz substrate (26 x 24 x 0.125mm) included E-plane probe waveguide to microstrip transitions, which formed hermetically sealed waveguide windows when the substrate ground plane was soldered to the box package [25].

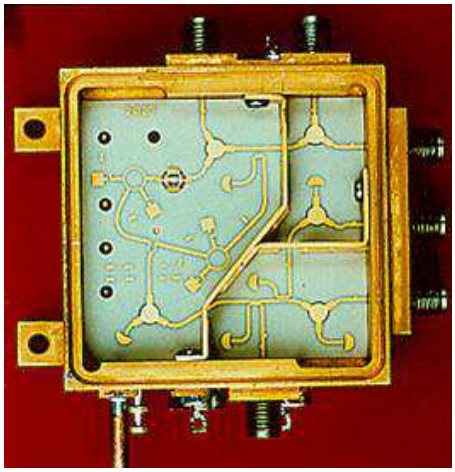

Fig.5. 1979 Ku-Band Tx-Rx Sub-System

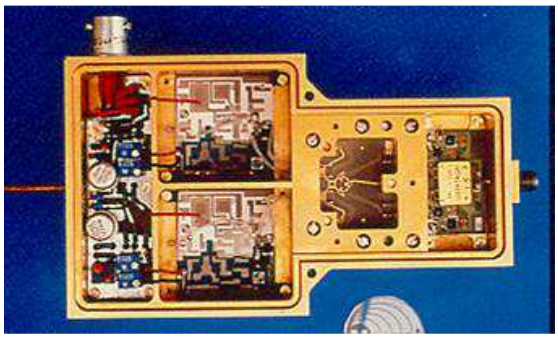

Fig.6. 1979 W-Band Integrated Sub-System

6. The 1980's

By the end of the 1970's, HRC had demonstrated the foundation of an MIC business and this was transferred to a GEC-Marconi Group for further business development, together with the majority of the hybrid MIC technology, where development continued (including projects in-hand) with many advanced components and sub-systems produced for commercial exploitation; much of the emphasis being at millimeter-waves to meet the increasing system interests for miniature integrated systems at these frequencies. This may best be demonstrated by a 94 GHz FM-CW transceiver contained within a volume of about 1 cubic inch [26], and a 94 GHz dual channel radar receiver/duplexer with a high level of integration i.e. incorporating some 17 circuit functions (including five ferrite insert non-reciprocal devices) on a single 18 x 18 x 0.12mm quartz substrate, with externally connected oscillator functions [27].

A major MMIC programme had been initiated at HRC in the late 1970's, resulting later in the formation of GEC Monolithics operating within GEC Research Ltd. As part of this programme studies were undertaken on diode based mixer circuits. Several diode balanced mixer circuits were demonstrated in the 1980's, in general based on the MIC design of two Schottky diodes with l.o. and signal inputs combined by a 3dB coupler. These for example included: (i) an 8-12GHz (i.f.10-500MHz) circuit, shown in Fig.7, with two finger (2 x 20µm) interdigital geometry diodes and a 3 dB Lange coupler on a 3 x 3mm x 200µm chip, providing a conversion loss of 6 dB [28]; and (ii) a 94GHz circuit, incorporating a rat race balanced mixer and l.o and signal WG coupling E-plane probes on a chip of 4 x 1mm,

with the diodes formed by a single air-bridged finger (1 x 5µm); the chip conversion loss was typically 7.5dB [29].

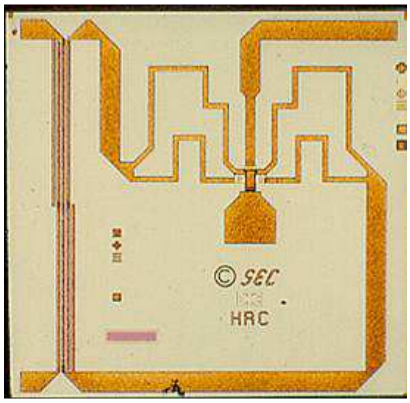

Fig.7. 8-12GHz MMIC Diode Balanced Mixer

7. Conclusions

This paper only briefly outlines some aspects of research and development that the GEC Research Laboratories, later GEC Hirst Research Centre, played in its internationally recognised leading role in the progress of mixer diode and associated circuit technologies, for the advancement of microwave receivers. Apologies are offered for the many omissions from this historical review.

Acknowledgements

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