LB-1045

A DRIFT TRANSISTOR FOR HIGH FREQUENCY APPLICATIONS

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OCTOBER 8, 1956

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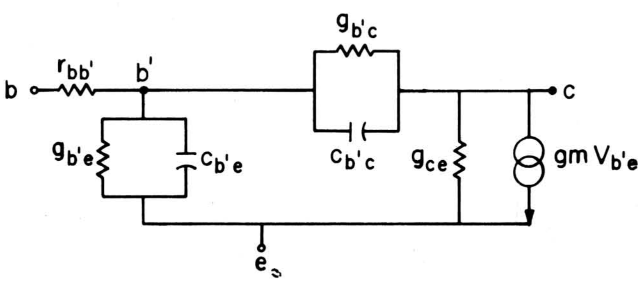
Approved

This bulletin describes a developmental drift transistor suitable for high frequency applications. Some constructional details along with applications are given. The high frequency figure of merit for this transistor is 132 mc.

Introduction

The drift transistor concept which was first published by H. Kroemer[1] in 1953 and the subsequent development of the technique of solid phase diffusion in semiconductors have greatly increased the high frequency potentialities of transistors. In particular, this bulletin describes a developmental drift transistor in which the useful frequency response has been increased by an order of magnitude over conventional junction transistors without appreciably changing the geometrical dimensions.



$$F.M. = \frac{1}{4\pi}\sqrt{\frac{1}{r_{bb'}\,C_{b'c}\,\tau}}$$

$R_{bb'}$ = *base lead resistance*
$C_{b'c}$ = *collector capacitance*
τ = *transit time*

$$\tau = \frac{W_b^2}{2D_p}$$

W_b = *base width*
D_p = *diffusion constant of holes*

$$R_{bb'} = \frac{\rho_b}{8\pi W_b}$$

ρ_b = *resistivity at base material*

$$C_{b'c} = \frac{A_c\,\epsilon}{10^{-4}\sqrt{\rho_b V_c}}$$

A_c = *collector area*
V_c = *collector voltage*
ϵ = *dielectric constant of Ge*

Fig. 1 — Hybrid π equivalent circuit of a transistor.

Fig. 1 shows the hybrid π equivalent circuit of a transistor, the commonly used high frequency figure of merit and the relationship of the critical parameters to the physical structure of the device. Qualitatively, the figure of merit expresses the fact that the transit time (τ) of minority carriers in the base produces a phase shift between emitter and collector current which decreases the gain by increasing the base current, the base lead resistance ($r_{bb'}$) attenuates the input signal and the collector capacitance introduces feedback from collector to base. Quantitatively, the figure of merit gives the frequency at which the power gain is reduced to unity.

The relationship of these parameters to the physical structure point out the practical design limitations. Since the base lead resistance is directly proportional to the resistivity (ρ) and the collector capacitance is inversely proportional to its square root, an optimum value of either of these parameters is never achieved. In practice, a fairly low resistivity material is used. However, material resistivity much less than 1 ohm-cm will not give satisfactory collector breakdown voltages. Attempts to decrease the transit time by decreasing the base width are limited by increasing base lead resistance and lowering of the punch-through voltage of the collector depletion layer to the emitter.

The Drift Transistor

The drift transistor structure not only reduces the interdependence of these characteristics but also provides a *built-in* field in the base that decreases the transit time. The distribution of impurities in a p-n-p drift transistor is shown in Fig. 2. In the base, the impurity density is large adjacent to the emitter junction and decreases until a small constant value is reached. The manner in which the graded impurity density produces a *built-in* field may be explained by considering the negatively charged majority carriers (electrons) and the positively charged impurity atoms associated with them. Since a gradient of free electrons exists, they will tend to diffuse to even out the distribution. However, any net motion of the negative charge leaves unbalanced the positive charge of the impurity atoms that are locked in the crystal structure. The charge displacement creates an electric field that exactly balances the electron diffusion so that equilibrium will be maintained. The direction of this field is such as to prevent electron diffusion from the high density area near the emitter to the low density area near the collector. Therefore, holes entering this region will be accelerated by the field from the emitter to the collector. For equal base widths and reasonable doping, the transit time in a germanium drift transistor can be reduced by a factor of four from that of a transistor which has a uniform base region[2].

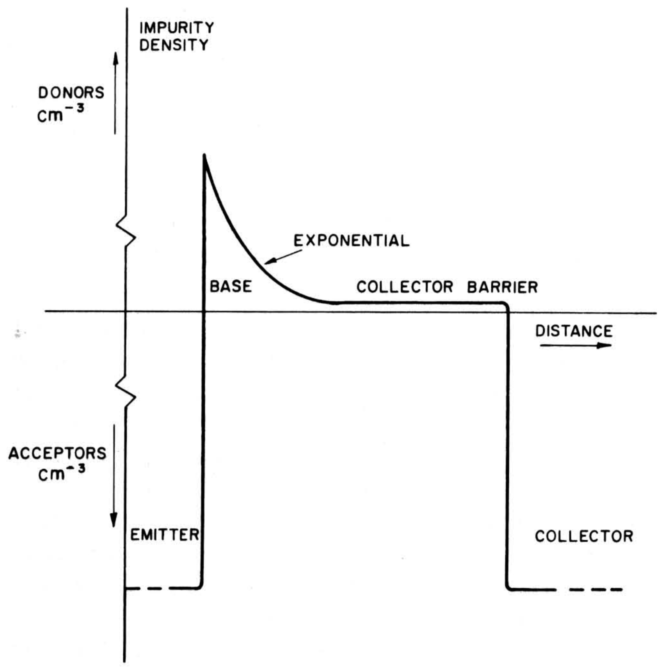


Fig. 2 – Impurity distribution in a p-n-p drift transistor.

In operation, the region of small constant impurity density is not considered to be a part of the base since for collector voltages above some critical value, called the starting voltage, the field produced by the collector voltage reaches through it.

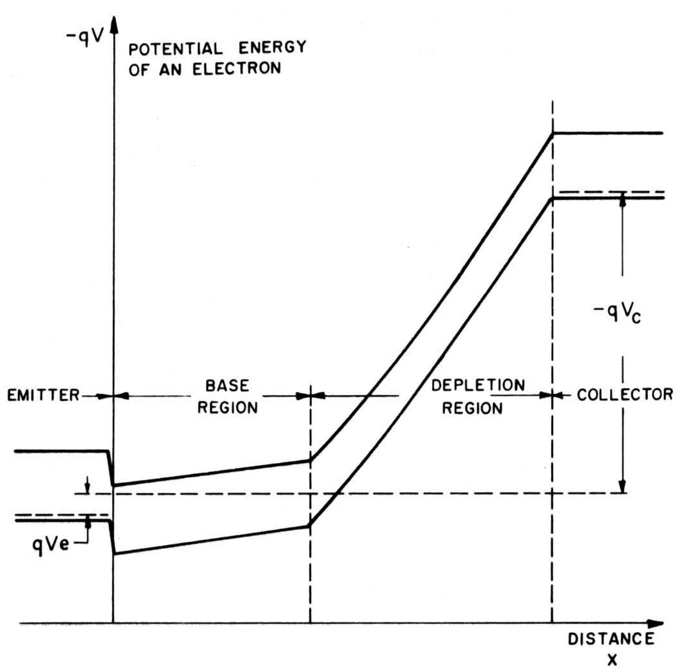


Fig. 3 – Potential distribution in a drift transistor.

The collector capacitance is not dependent on the resistivity in the base adjacent to the emitter since its value is determined by the width of the depletion layer, which in this case is determined by the width of the constant high resistivity region. Furthermore, the wide collector depletion layer tends to give a high collector breakdown voltage which is also not affected by the base resistivity. The average resistivity in the base region may now be made extremely low without appreciably affecting either of the above mentioned parameters and since the base lead resistance is proportional to the resistivity, it can be made small even for small base widths. A consequence of this low base resistivity is a low emitter breakdown voltage. However, in amplifier circuits where the emitter is forward biased, this low breakdown voltage is of no importance.

A diagram of the potential distribution in a drift transistor with terminal voltages applied is shown in Fig. 3. The slope of the potential indicates the relative magnitude of the fields present in the base and collector depletion layer. Because of the high field in the depletion layer, the transit time of carriers through it is negligible compared to the transit time in the base.

Construction

The RCA developmental type drift transistor is constructed in essentially the same manner as an ordinary alloy junction radio-frequency unit except that solid phase diffusion is incorporated to obtain the graded impurity region. In the diffusion technique, high resistivity n-type germanium is heated nearly to its melting point in the presence of a controlled arsenic atmosphere. Arsenic atoms are dissolved at the surface of the germanium and, because of their mobility in the solid material at high temperatures, diffuse into the interior of the crystal. If the surface concentration of arsenic is held constant, the impurity distribution in the graded n-type skin produced on the crystal is that of the complementary error function shown in Fig. 4. The dotted line in Fig. 4 is the sum of the diffusing impurities and those originally present in the host crystal. This variation of impurity concentration with distance is a good approximation to the idealized one shown in Fig. 2. The width of the graded region is determined by the temperature and time of diffusion and the surface concentration of the diffusing impurity. The arsenic, of course, diffuses into the crystal from both sides. Selective etching is then used to remove the graded region on one side.

Both the emitter and collector junctions are made by the commonly-used alloy technique. For the emitter an *In, Ga, Zn* alloy is used and the depth of penetration into the graded region is adjusted to obtain a maximum field in the base without harming the collector to base current transfer ratio. The addition of *Ga* to the alloy further insures a high current transfer ratio. The collector junction is formed by alloying an *In, Zn* dot into the constant high resistivity material on the opposite face of the germanium pellet. The major consideration in the collector alloying is that the depth of penetration be adjusted to obtain a collector barrier width consistent with the desired collector capacitance.

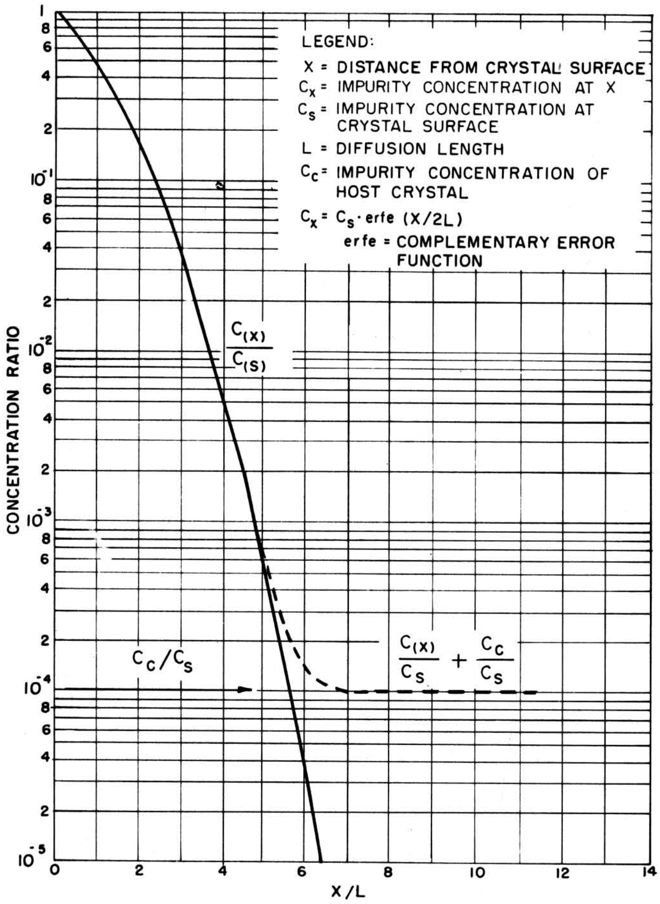


Fig. 4 – Impurity distribution after solid phase diffusion.

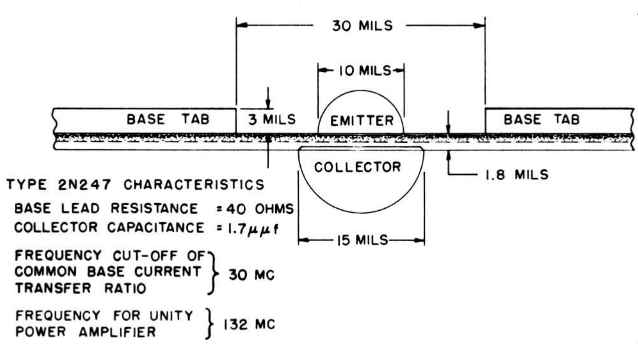
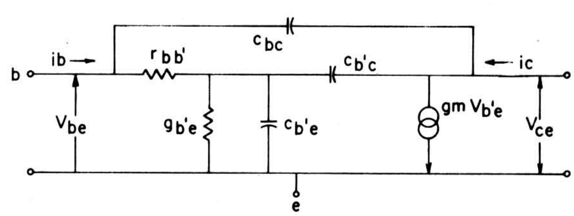


Fig. 5 – Cross sectional drawing of a drift transistor.

The cross sectional drawing in Fig. 5 shows the general physical construction of the device and its pertinent dimensions. Its appearance is much the same as that of a conventional alloy junction transistor except that the emitter side of the crystal has been shaded to indicate the graded impurity region. A ring type base connection has been used to obtain as low a value of base lead resistance as practical. Also shown in Fig. 5 are the characteristics of this developmental drift transistor, as determined from an average of a large number.

Characteristics

From the foregone discussion of device characteristics, it is evident that the drift transistor is quite useful in extending the frequency range of useable amplification over that obtainable from the conventional alloy junction transistor. An electrical presentation of the equivalent circuit[3] of the drift transistor is shown in Fig. 6 which information relates directly to its frequency capabilities. This figure and accompanying hybrid π parameters describe the device in a one generator equivalent circuit which applies over the useful frequency range of the transistor. From these parameters at a given operating point, the input and output impedance and maximum power gain may be computed. The equivalent circuit shows that the input circuit consists of a low pass filter ($r_{bb'}$ and $C_{b'e}$) which values determine to a first approximation the gain versus frequency capabilities of the device. The equivalent circuit also shows that the output circuit is not isolated from the input circuit because of the feedback capacitance $C_{b'c}$; the effects of this internal feedback may be readily neutralized.



Hybrid π Parameters

Derived from the generator equivalent circuit and apply over the useful frequency range of the transistor

Resistance $r_{bb'}$	40 ohms
Conductance $g_{b'e}$	640 μmhos
Capacitance $c_{b'e}$	200 μμf
Capacitance $c_{b'c}$	1.7 μμf
Intrinsic transconductance, g_m, (I_e = 1ma)	37,000 μmhos
Frequency for unity power amplification	132 mc.
Interelectrode capacitance c_{bc}	0.5 μμf
Maximum 10 mc power gain	24 db
Input resistance (at. 10 mc)	170 ohms
Output resistance (at 10 mc)	4,500 ohms

Fig. 6 – Equivalent circuit of a drift transistor.

When the use of this device is contemplated for r-f amplification, consideration must be given to the magnitude of the d-c collector voltage. Fig. 7 shows the effect of collector voltage on alpha cutoff. If too low a supply voltage (below 4 volts) is used the obtainable power gain at the higher frequencies will be lowered. Fig. 8 shows the effect of emitter current on alpha cutoff.

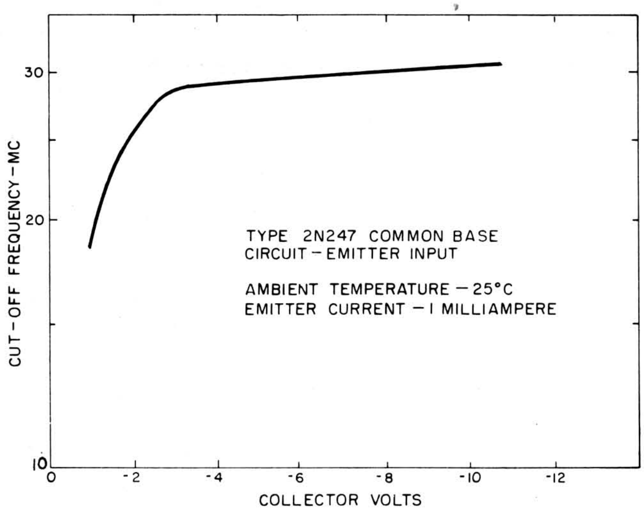


Fig. 7 – Effect of collector voltage on alpha cutoff.

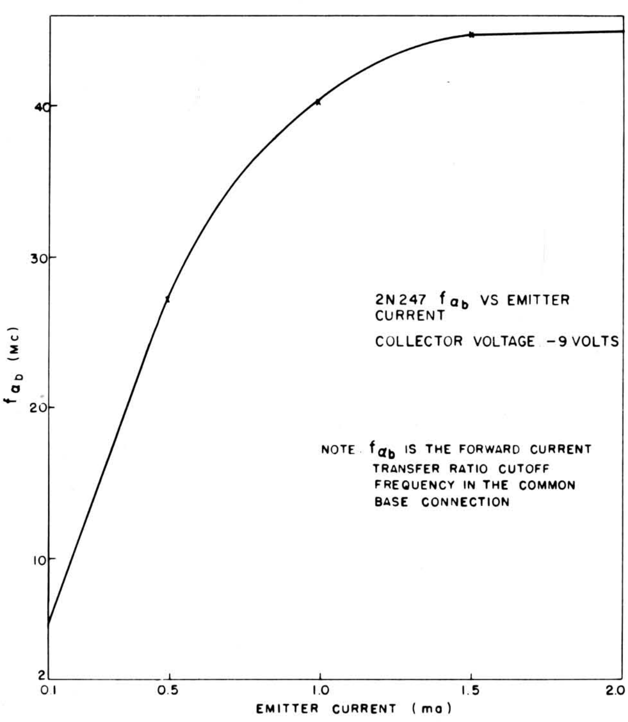


Fig. 8 – Effect of emitter current on alpha cutoff.

The useful power gain of the drift transistor may be shown by reference to Fig. 9. Curve 1 shows the maximum neutralized power gain vs frequency. A value of 47 db is obtained at 1 mc, and thereafter the gain decreases at a 6 db per octave rate to approximately 0 db at 136 mc (which is the high frequency figure of merit). Curve 2 shows the useable neutralized power gain (at $I_e = 1ma$) when regard is given to stability and interchangeability considerations. This curve shows a useable power gain of 37 db at 455 kc and decreases at a 3 db per octave rate to 11 mc where it then follows the 6 db per octave rate of the maximum power gain curve. Curve 3 shows the unneutralized power gain calculated for stability and interchangeability of transistors. This curve shows a power gain of 33 db at 455 kc and also decreases at a 3 db per octave rate to 25 mc.

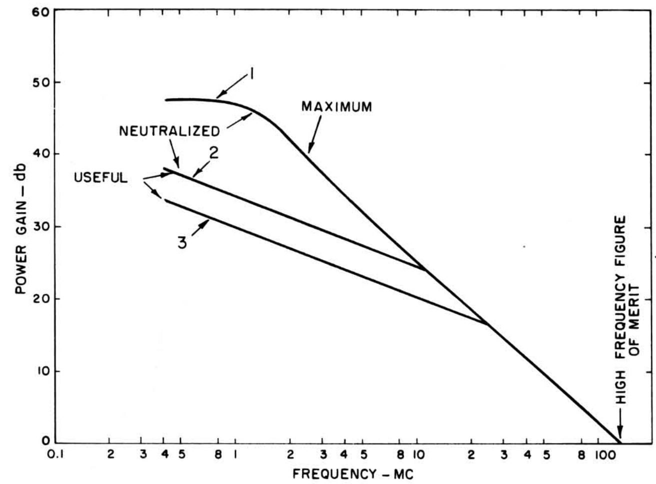


Fig. 9 – Useful power gain curves for a drift transistor.

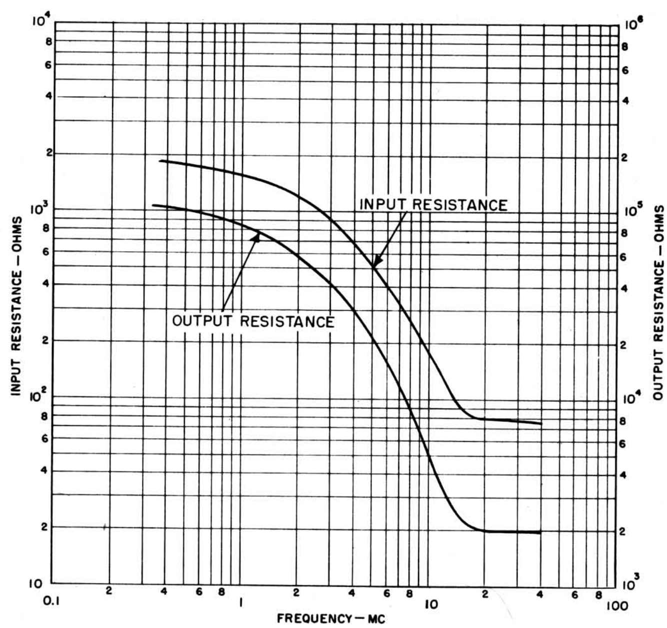


Fig. 10 – Input and output resistance curves for a drift transistor.

To facilitate the design of circuits capable of the above power gain at the desired frequency it is necessary to know the input and output resistance for this frequency as shown in Fig. 10. These curves show that the input and output resistance vary from $R_{in} = 1350$ ohms and $R_{out} = 100{,}000$ ohms at 455 kc to $R_{in} = 170$ ohms and $R_{out} = 4500$ ohms at 10.7 mc.

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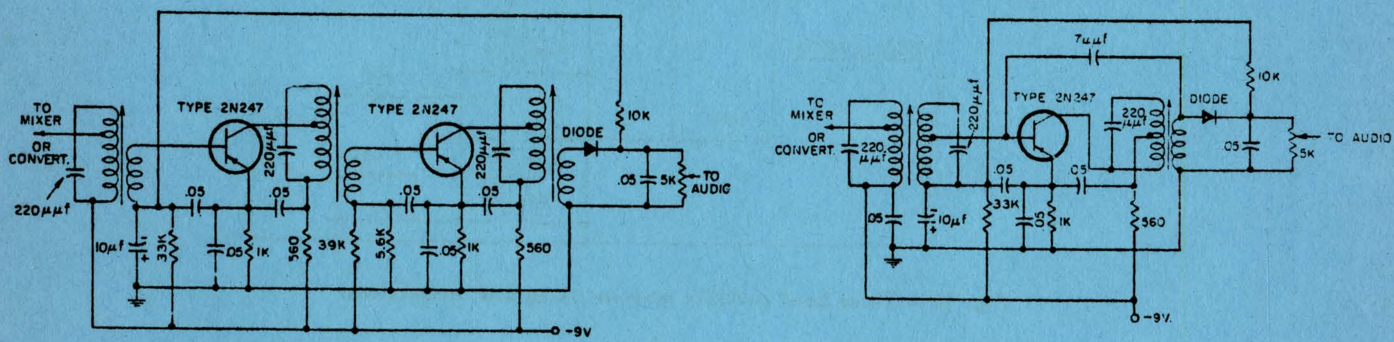


(a) TWO STAGE UNNEUTRALIZED 455KC IF AMPLIFIER

(b) ONE STAGE NEUTRALIZED 455KC IF AMPLIFIER

Fig. 11 – Drift transistor 455kc i-f amplifiers.

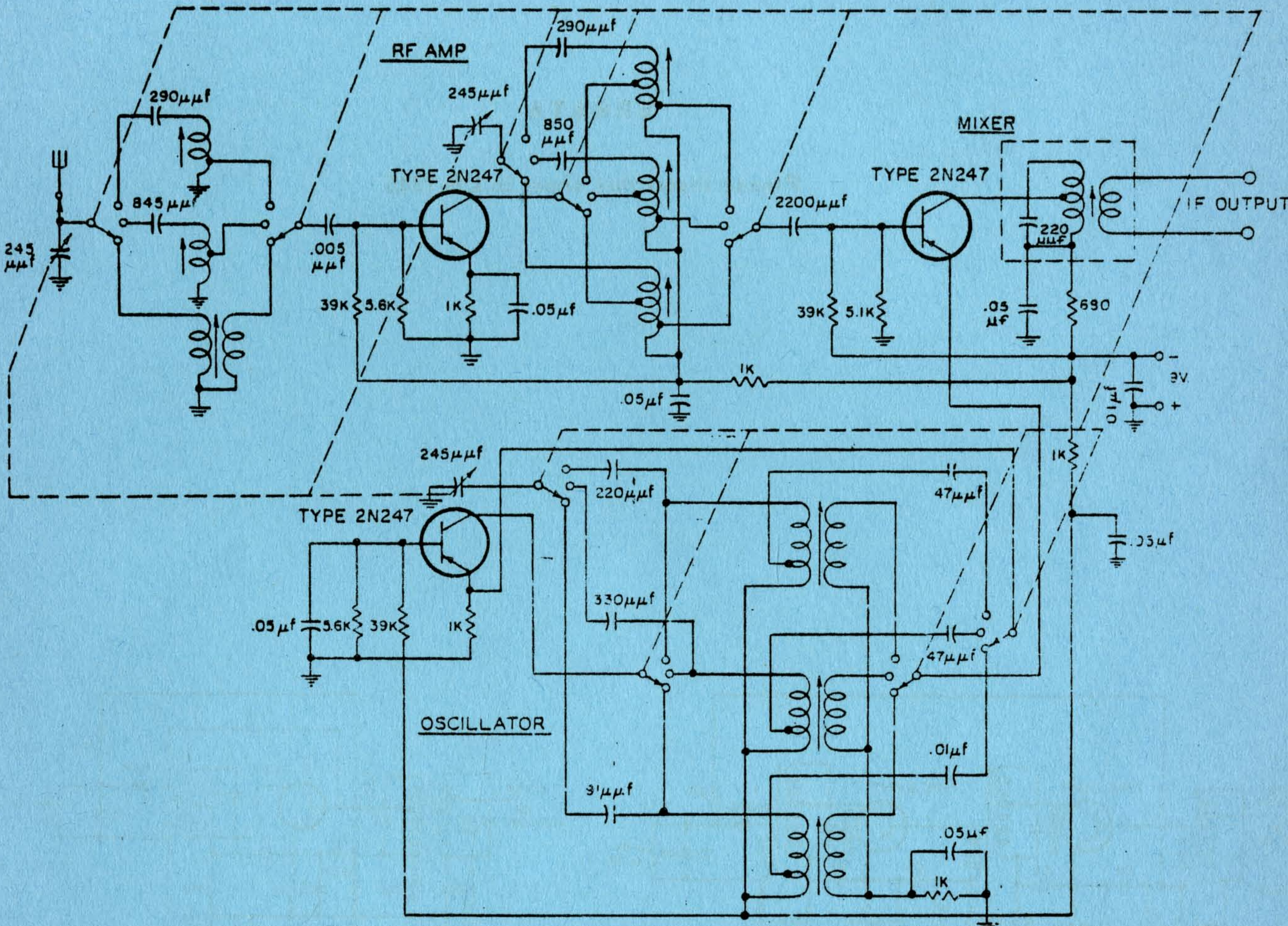
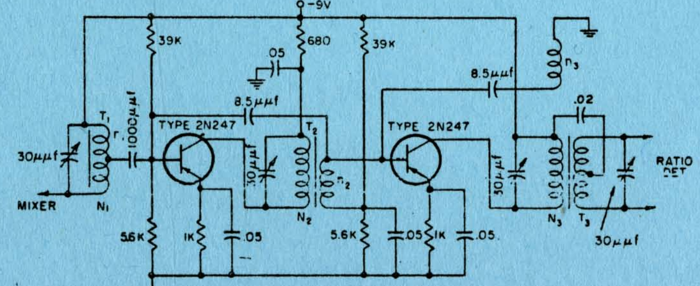


Fig. 12 – Three band portable receiver using drift transistors.



$N_1 = N_2 = N_3$ FOR L TO TUNE WITH 30μμf AT 10.7 MC

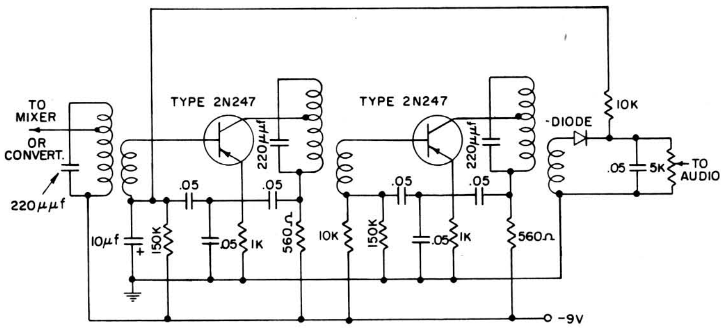
$T_1 = T_2 = T_3 = 5$ T=TURNS RATIO PRIMARY TO TAP OR SECONDARY

Fig. 13 – 10.7 Mc i-f amplifier using drift transistors.

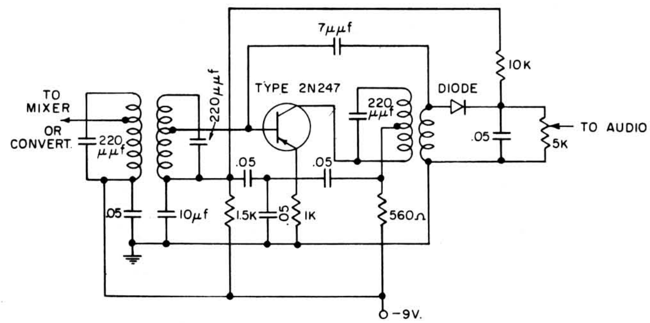
Applications

One of the typical applications for the drift transistor is in a 455 kc i-f strip. An example of a two stage unneutralized design is shown in Fig. 11a. This two stage i-f amplifier strip will provide 66 db of gain. A single stage neutralized i-f amplifier is given in Fig. 11b. This later amplifier will provide 37 db of gain including transformer losses and with complete stability and interchangeability of transistors.

Another typical application as shown in Fig. 12 is a three band portable radio receiver covering the broadcast (540-1630 kc) and short wave bands (4.75 – 11 mc and 10 – 23 mc). This circuit utilizes the drift transistors as r-f amplifier, mixer, and separate oscillator, to obtain the amplification and frequency conversion from the r-f frequency down to 455 kc. The use of an r-f amplifier is recommended for the short wave bands in that it provides an acceptable image rejection ratio with sufficient gain at the high end of the short wave band to warrant its use



(a) TWO STAGE UNNEUTRALIZED 455KC IF AMPLIFIER



(b) ONE STAGE NEUTRALIZED 455KC IF AMPLIFIER

Fig. 11 – Drift transistor 455kc i-f amplifiers.

TABLE I

Coil Data for *RF* and Converter Stages of Fig. 12

Coil	Antenna			Interstage			Oscillator		
	BC	*4.5 – 11.5 MC*	*10.5 – 23*	*BC*	*4.5 – 11.5*	*10.5 – 23*	*BC*	*4.5 – 11.5*	*10.5 – 23*
Primary turns	95	23	16	200	23	16	200	23	16
1st tap - turns from bottom		4	3	20	4	3	20	3	3
2nd tap - turns from bottom				100	12	8			
Secondary turns	5						10	1	1
Wire size	10/38 Litz	#26	#26	7/41 Litz	#26	#26	7/41 Litz	#26	#26
Coil Dia. (inside)	0.33"	5/8"	3/8"	1/2"	5/8"	3/8"	1/2"	5/8"	3/8"
Coil Length	4" on 8" × 0.33" Ferrite Rod	11/16"	1/2"	3/4"	11/16"	1/2"	3/4"	11/16"	1/2"

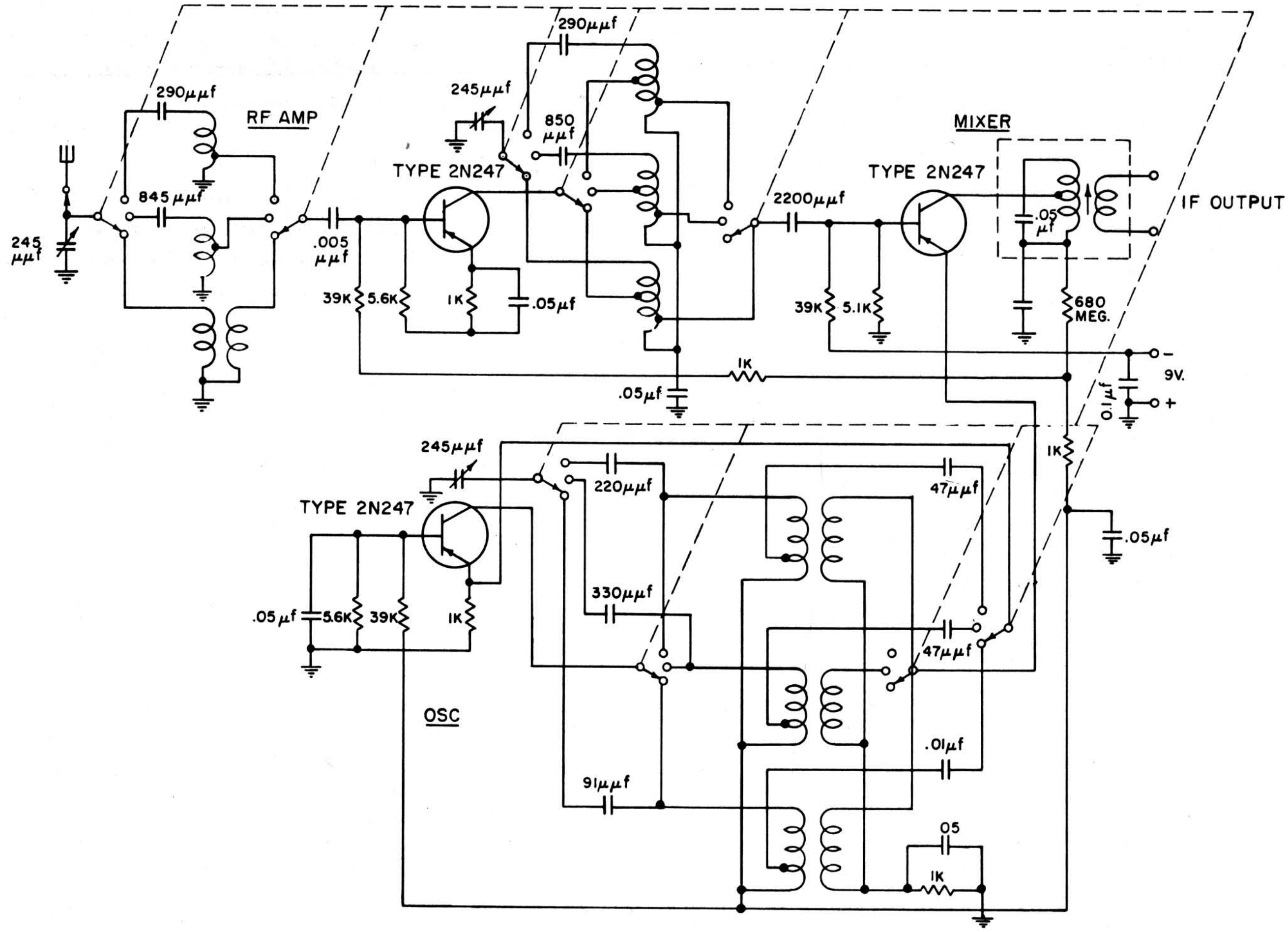


Fig. 12 – Three band portable receiver using drift transistors.

in this application. On the 10 to 23 mc band, it is advantageous to conjugate match the r-f transistor at the input and output at the high end of the band thereby obtaining the highest gain where the transistor is down in gain. The oscillator circuit is conventional and operated by virtue of positive feedback from the collector tank to the emitter through a condenser. The oscillator injection for all three bands is approximately 0.1 volt into a secondary placed in the emitter circuit of the mixer. The r-f and oscillator signals are present in the base emitter circuit and produce a mixing action resulting in the useful difference frequency of 455 kc. The overall power gain of the front end from r-f to i-f in the high band (10 to 23 mc) is approximately 32 db, the medium band (4.75 to 11 mc) approximately 36 db, and the broadcast band (540 to 1620) approximately 55 db. Coil data for this circuit are given in Table I.

The next circuit shown in Fig. 13 is an i-f amplifier strip at 10.7 mc (the FM intermediate frequency). Since at 10.7 mc the maximum neutralized power gain of the transistor can be utilized the design represents practical high efficiency transformers with 0.24 db loss per transformer. The transformers are also designed to have an overall i-f bandwidth of 200 kc. The power gain achieved using this circuit is approximately 47 db from the input to the ratio detector.

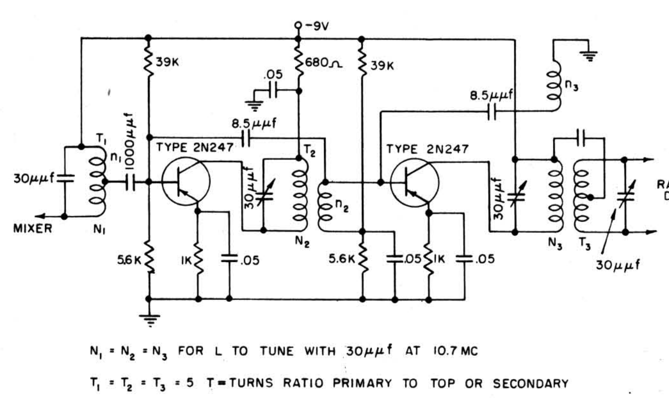


Fig. 13 – 10.7 Mc i-f amplifier using drift transistors.

Conclusion

This bulletin described a developmental drift transistor and a few of its most important applications. The application of this device to the entertainment field as well as communications and military equipment offers excellent possibilities for the reduction of overall size, weight, and battery power consumption that transistors permit. Also, the performance of this device at high frequencies should result in commercial acceptance of equipment designed around the drift transistor.

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