Transistor Meter

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Business Field:

- Semiconductor Quality Assurance support in Japan for foreign semiconductor company
- Analog related Circuit Design

Book:

TITLE: Operational Amplifier Specifications and Applications (Japanese)

This book refer operational amplifier specification, measurement method and application of the specification. This book covers DC/AC/Noise specifications. "Application of the specification" mean calculation method of errors on the application circuit. This book also has some suggestions of calculation method and measurement method for cases that difficult to calculate from ideal models, "know-how" in other words. 452 pages.

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The Transistor Meter mean Transistor characteristics test equipment. This meter use for DC and (270[Hz] to 1000[Hz] of) AC small signal testing for BJTs, JFETs, MOSFETs and Dual gate FETs.

The feature of the meter is, DUT works in the negative feedback loop. From this, appropriate bias of the DUT apply from driving amplifier with automatically.

This meter has an oscillator and this oscillator shakes DUT operating condition with small AC signal and measure DUT parameters. From measurement results, you can calculate AC h-parameters (hybrid parameters), gm (mutual conductance) and $|y_{fs}|$ (FET) for example.

Small signal BJTs and FETs are use for a circuit that expose higher voltage spikes (ex. ignition of the vehicle and Electric Static Discharge at input/output of the equipment). And also cite low-cost products or products that has long term of life cycle.

If you have performance failure of transistor circuit, you can find the mechanism smoothly when you have transistor meter. The transistor meter use for these situations.

Unfortunately, this is difficult project for beginners, because an error of the AC measurement occur by stray capacitance.

The major issue of this document is building transistor meter. I'll publish mathematically things (ex. How to calculate h-parameters?) in another document.

The purpose of this document is the advertisement of my business. From this background, I cannot bear the responsibility for your inconvenience, loss and damage even if caused by any inaccurate expression and any defect of the document.

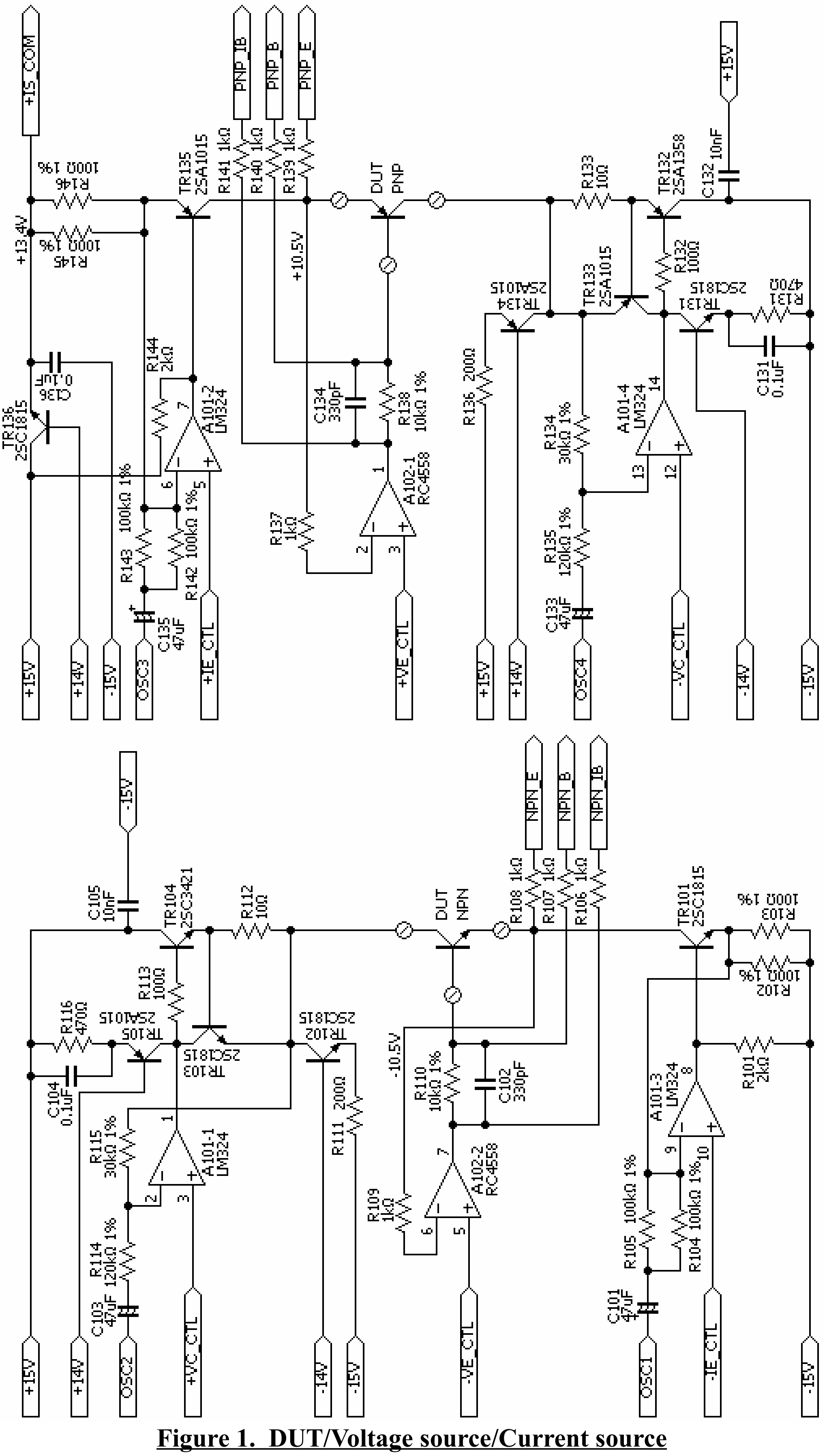


Figure 1. DUT/Voltage source/Current source

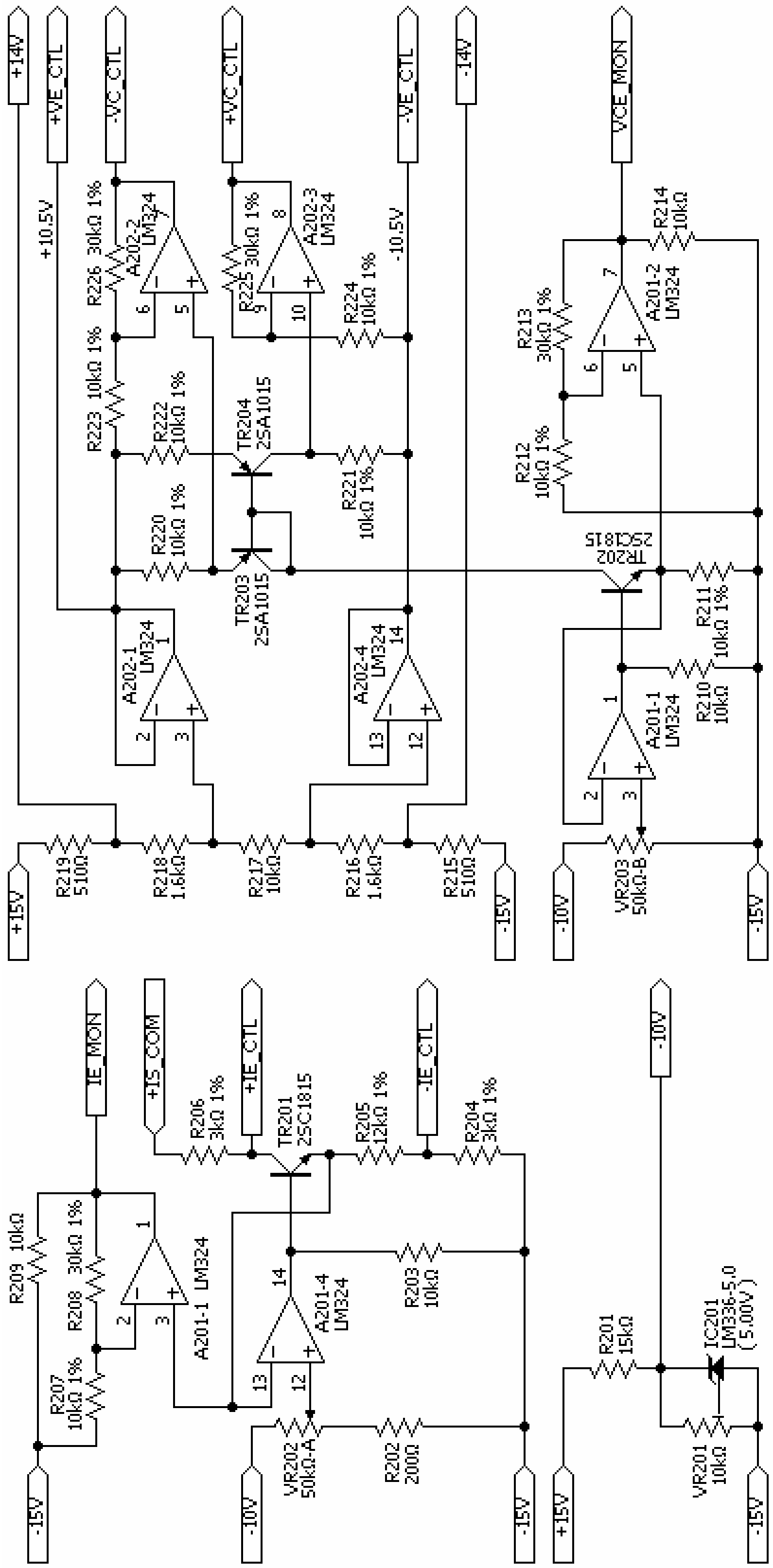


Figure 2. Current source/ Voltage source Controller

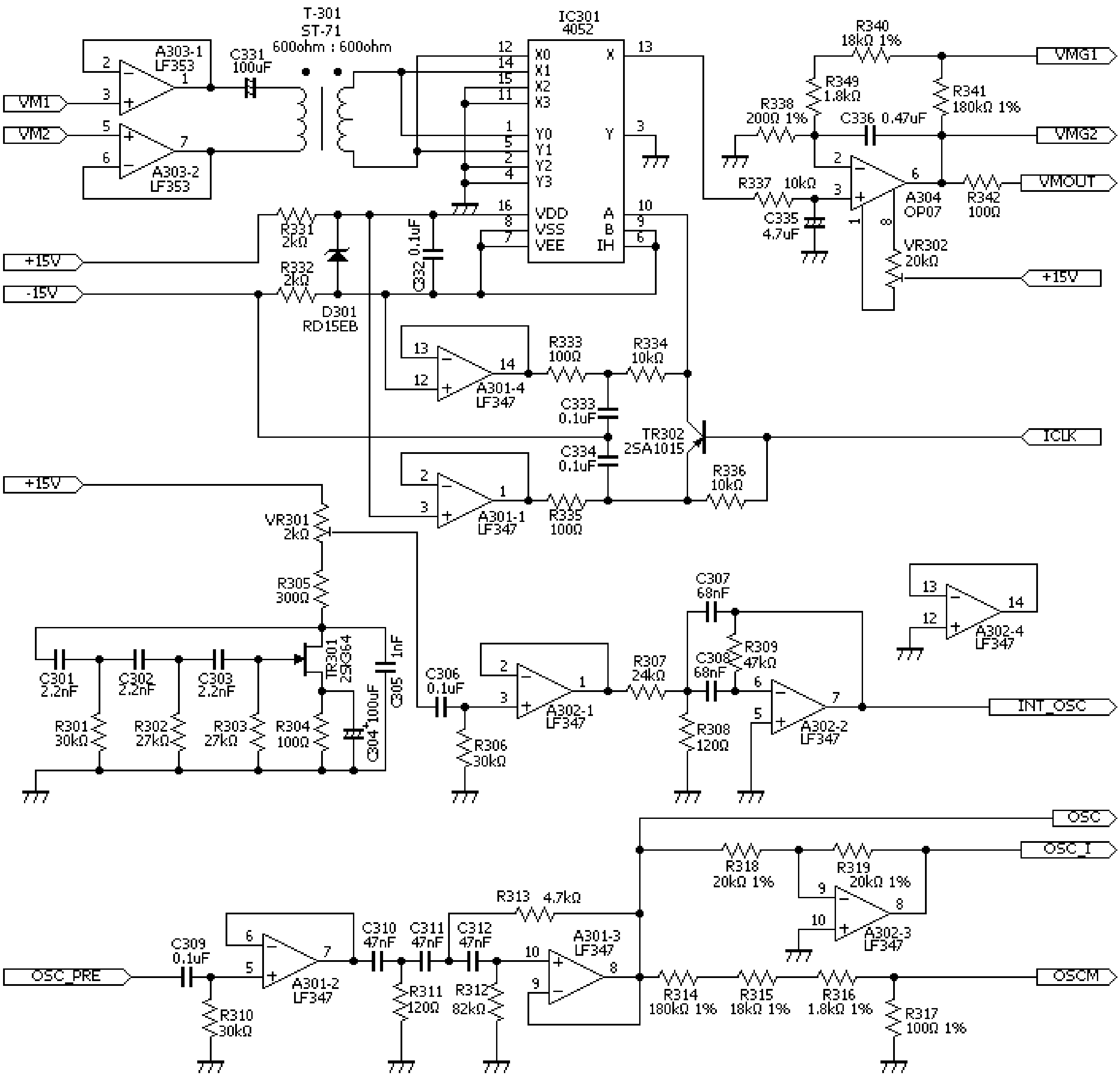


Figure 3. AC measurement Circuit

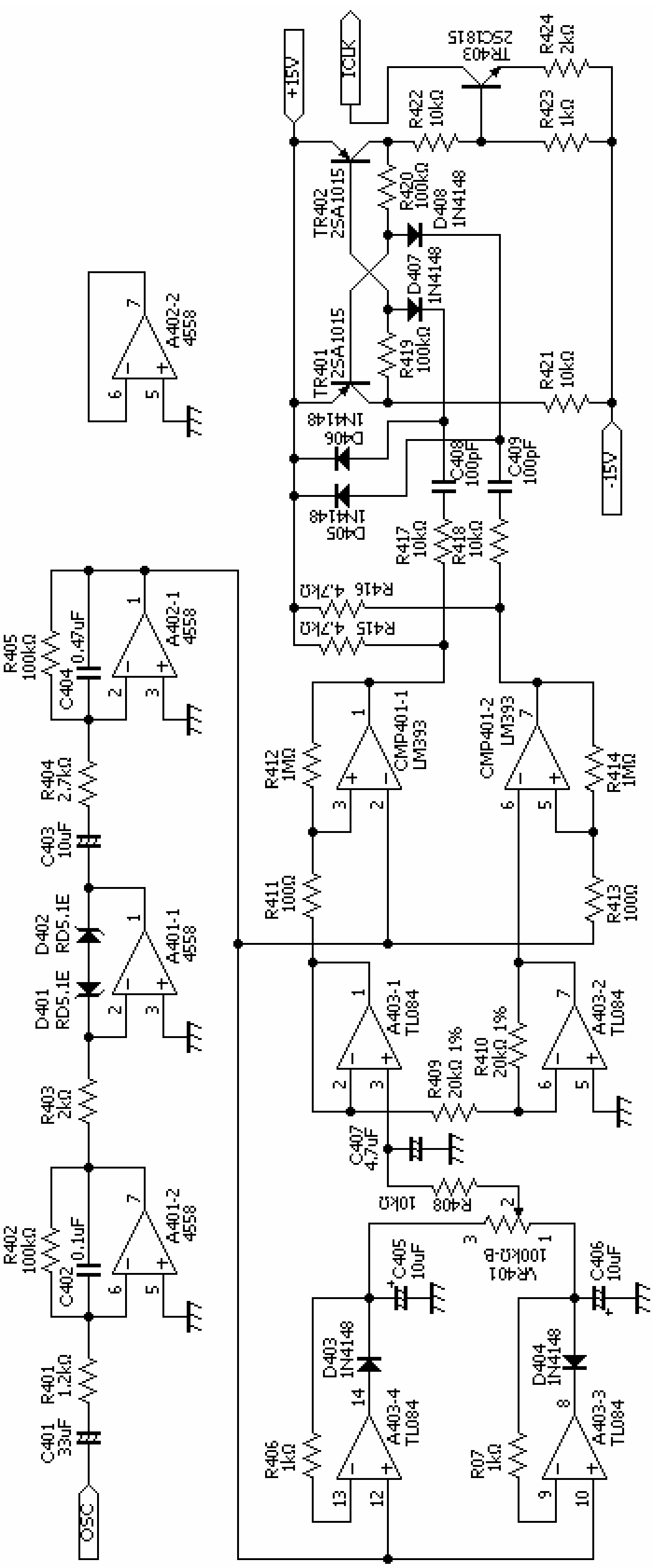


Figure 4. Phase shifter

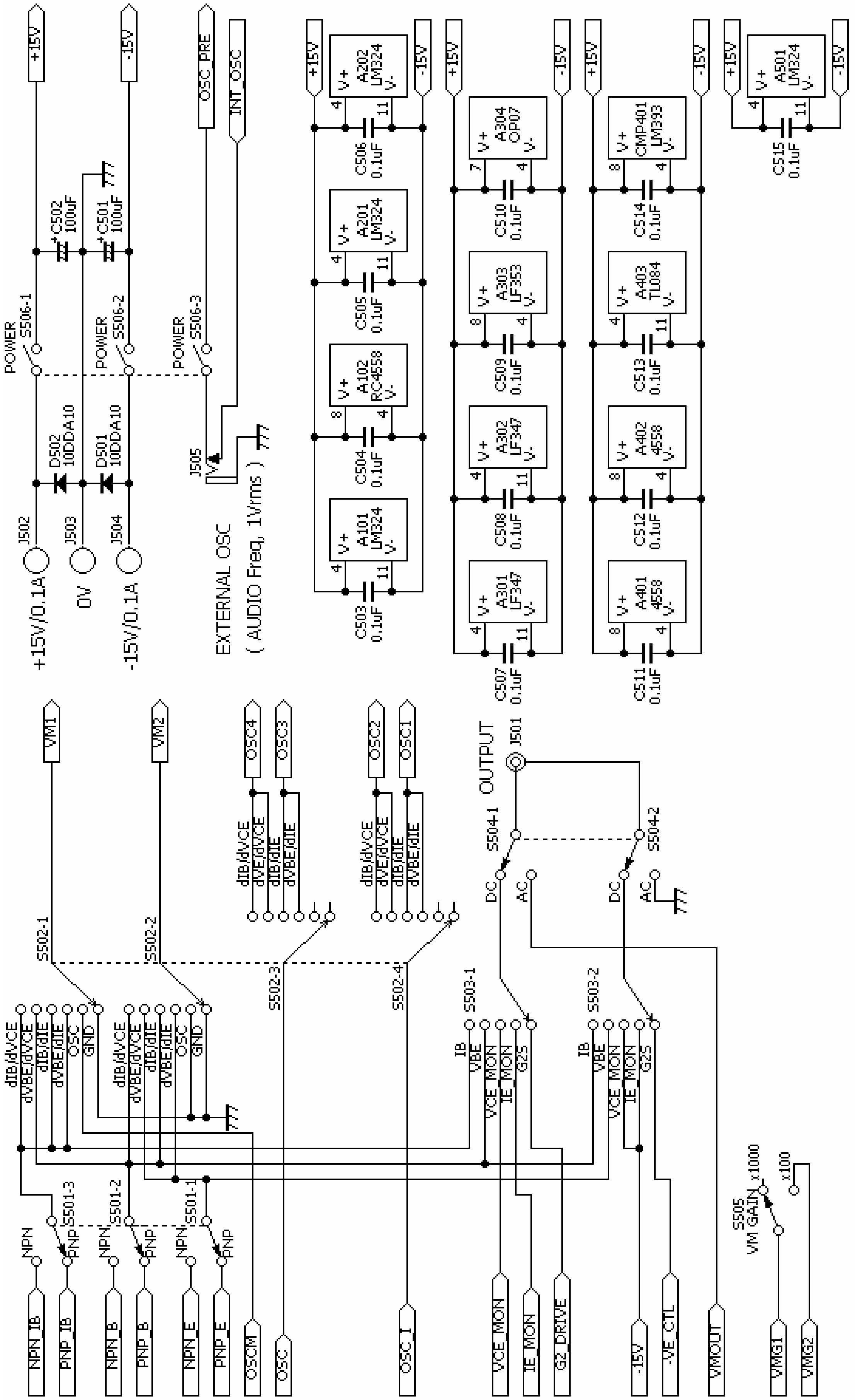


Figure 5. Switch/Power supply

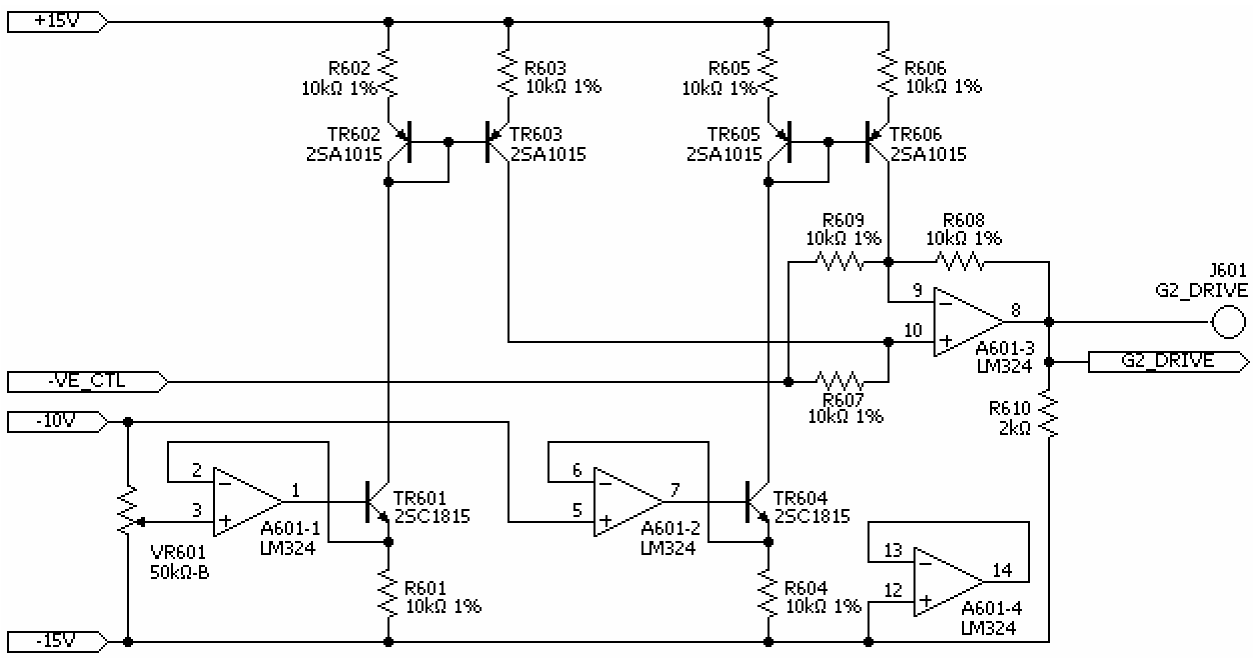


Figure 6. Gate drive circuit for Dual gate FETs

Theory and Operation

Figure 1 - **6** are all of circuit diagrams of the transistor meter. About the parts number in the diagram, the position of hundred coincide to figure number basically. So the parts number coincide to this rule, omit the figure number in the sentence. And circuit diagram use "u" for "micro"

Let's start explanation about the theory of the operation with **Figure 7 a/b**.

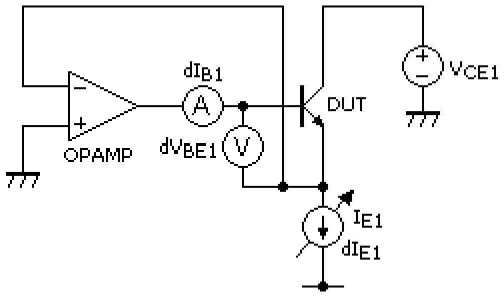


Figure 7 a. Test for Emitter Current shaking

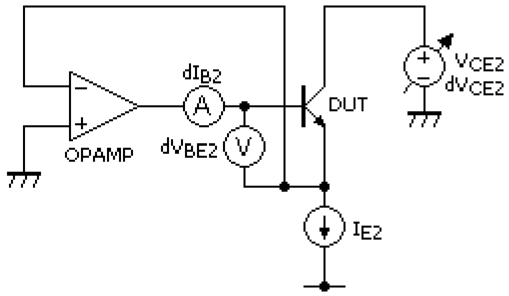


Figure 7 b. Test for Collector-Emitter Voltage shaking

Figure 7 a/b indicates to shake operating condition with AC small signal that superimposed on DC bias (dI_{E1} and dV_{CE2}). At the this condition, measure Base input current change (dI_{B1} and dI_{B2}) and Base - Emitter voltage change (dV_{BE1} and dBV_{E2}). This is AC measurement method, you can measure DC parameters with complete DC operating condition (No shaking) also.

You should make an image of DUT operation in **Figure 7 a/b**.

DUT works in negative feedback loop that using an operational amplifier. In static state of the negative feedback loop and DUT works under forward bias condition, DUT Emitter voltage is the same as non-inverting input voltage of the operational amplifier (=0[V]).

The reference voltage of the Collector voltage (V_{CE1} or V_{CE2}) is 0[V](=GND). So Collector voltage means Collector - Emitter voltage.

Emitter connect to the current source (I_{E1} or I_{E2}). From this, Emitter voltage keep to 0[V] by negative feedback loop and you can set any DC Emitter current.

Base connect to the operational amplifier output. In this situation, Base voltage optimize with negative feedback loop. Transistor has the character of "When determine V_{CE} and I_E, V_{BE} and I_B settle at specific value" An expression from another direction is "You cannot set V_{CE}, I_E, V_{BE} and I_B with independently" From this character, Negative feedback loop settle at optimized condition with automatically.

This is DUT operation in the negative feedback loop.

Next is the outline of the measurement.

Figure 7 a is, apply dI_{E1} (~20[μA]) and measure dI_{B1} and dV_{BE1}. **Figure 7 b** is, apply dV_{CE2} (~0.25[V]) and measure dI_{B2} and dV_{BE2}. From these measurement, we can get following four parameters:

dI_{B1}/dI_{E1}, dV_{BE1}/dI_{E1}, dI_{B2}/dV_{CE2}, dV_{BE2}/dV_{CE2}

h-parameters calculate from these parameters for example.

Figure 8 is the h-parameter of 2SC1815GR (one of popular transistor in Japan). You can compare with datasheet easily because of the same format.

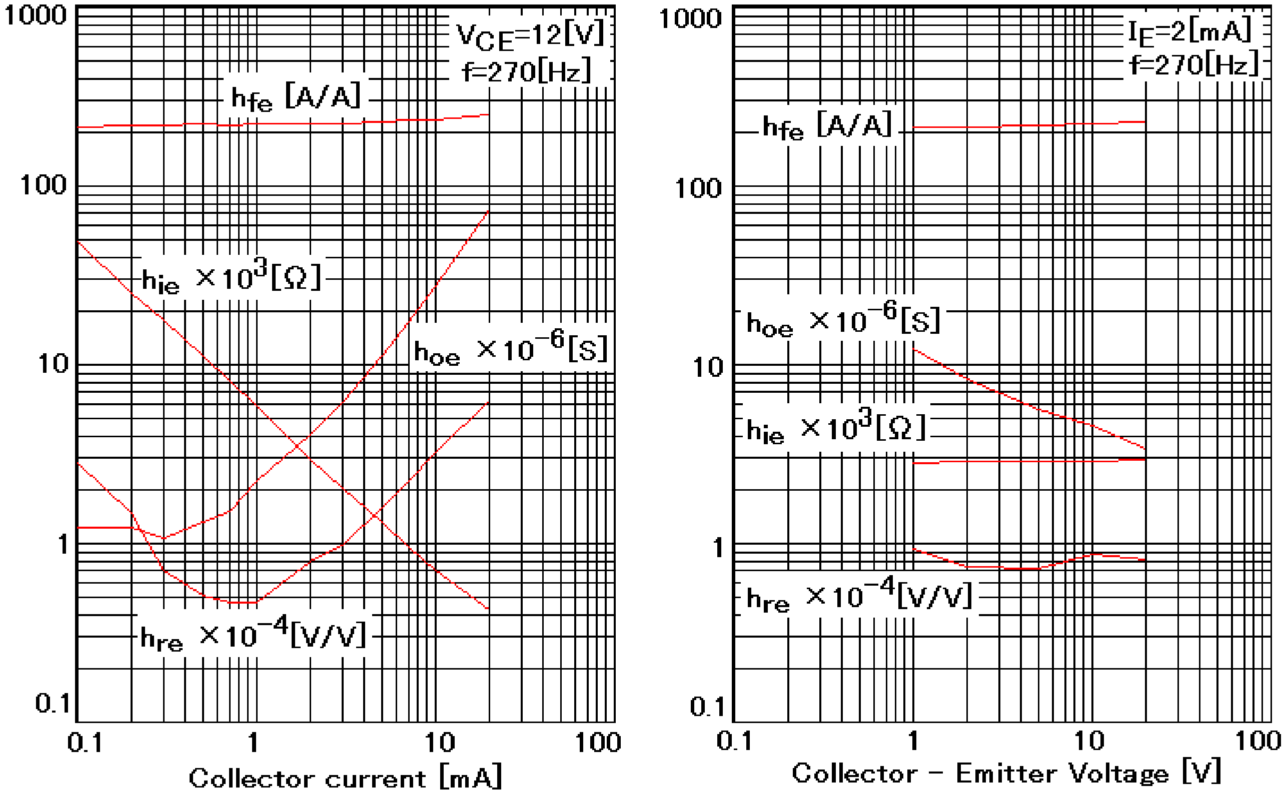


Figure 8 2SC1815GR AC h-parameter Test Results

I got similar data. However there are some difference. For example, right side graph doesn't have rising characteristic around V_{CE}=1[V]. I think the reason of this is the different value of dV_{CE2} in **Figure 7b**. This meter use 0.25[V] for dV_{CE2}, so transistor still have some margin of the operation at V_{CE}=1[V]. In another fact, I confirmed rising characteristic at V_{CE}=0.7[V].

There are another some small difference in the plot. I think if you need accurate h-parameter value, you should use the same test method as h-parameter measurement. This meter focusing characteristics measurement of BJTs and FETs with simple circuit and simple operation.

You can get some parameters of the SPICE model from this meter. And you can get gm and output resistance with any operating conditions also.

AC Test Circuit

Here is explanation of signal flow on circuit diagrams and operation for getting four parameters (dI_{B1}/dI_{E1}, dV_{BE1}/dI_{E1}, dI_{B2}/dV_{CE2}, dV_{BE2}/dV_{CE2}).

At first, negative feedback circuit that contained DUT is in **Figure 1**. Negative feedback loop consist of A102-1 (for PNP-BJT or Pch-FET), A102-2(for NPN-BJT or Nch-FET) and DUT. From **Figure 1**, NPN and PNP circuit works independently. At the test, NPN or PNP select with S501, DUT power is always ON (S501 is just switch for measurement circuit).

The voltage of non-inverting input of A102-1 is +10.5[V], and A102-2 of that is -10.5[V] from GND (0[V] of the power supply voltage). From this setting, this meter covers 0 to 20[V] of V_{CE} with ±15[V] of power supply voltage.

dI_{B1} and dI_{B2} in **Figure 7**, these Base current measure with voltage drop at R110 and R138 (10[kΩ]). dV_{BE1} and dV_{BE2} in **Figure 7**, these voltage measure directly through 1[kΩ] of buffering resistors.

V_{CE} is generated by A101-1 (for NPN-BJT or Nch-FET) and A101-4 (for PNP-BJT or Pch-FET) with boost transistors.

The range of V_{CE} is 0 to 20[V] (refer to DUT Emitter voltage). Both (PNP and NPN) of V_{CE} is adjusted by VR203. So you cannot adjust different V_{CE} between NPN and PNP.

dV_{CE} in **Figure 7** is generated by sine wave voltage that apply to OSC2 of A101-1 or OSC4 of A101-4. This sine wave voltage get from TR301 (oscillator), or EXTERNAL OSC in **Figure 5**. The amplitude of sine wave voltage is 1[V] at OSC2 and OSC4. dV_{CE} is -1/4 times OSC2 or OSC4 input voltage (=-0.25[V]). Minus sine means inverting.

I_E is generated by A101-3 (for NPN-BJT or Nch-FET) and A101-2 (for PNP-BJT or Pch-FET) with transistors (TR101 and TR135).

The range of I_E is 0.1 to 20[mA]. Both (PNP and NPN) of I_E is adjusted by VR202. So you cannot adjust different I_E between NPN and PNP.

dI_E in **Figure 7** is generated by sine wave voltage that apply to OSC1 of A101-3 or OSC3 of A101-2. The source of the sine wave voltage is the same as explanation of V_{CE} (TR301 oscillator or EXTERNAL OSC). 1[V] of sine wave voltage convert to 20[μA] of sine wave current with R104|| R105 or R142||R143 (50[kΩ]).

Figure 3 is sine wave oscillator and AC voltage measurement circuit.

Oscillator is a phase shift oscillator that using TR301. When you try building this oscillator, you may take time to tuning of component value for getting frequency and low distortion sine wave.

I believe you can use square wave that has 50% of the duty cycle from my experience. My first design doesn't have BPF (Band Pass Filter) that consist of A302-2. Before add BPF, I performed tuning of the oscillator (TR301). I use this oscillator at the moment, so I don't have use square wave. However during evaluation of BPF on the bread board, I applied square wave and I confirmed low distortion sine wave. From this reason, I believe you can use square wave. Please mind, I don't use square wave.

If you have an external oscillator, you can remove internal oscillator.

Oscillation frequency is 980[Hz]. Why is not 1[kHz]? is avoiding harmonics of AC power line frequency. In Japan, we have two different power line frequencies (50[Hz] and 60[Hz]) depending on area (east or west). When avoid harmonic frequency for both of frequencies, 980[Hz] is one of choice. Why we have to avoid harmonics? is, this meter measures micro-volt level of small voltage. So when you use external oscillator, you should mind this mechanism when you choose frequency.

The oscillator output voltage level adjust to 1[V] with VR301.

Oscillator output voltage go into A302-2 (BPF) through A301-1 (buffer amplifier). The reason of BPF is getting low distortion sine wave. This meter use PSD (Phase Sensitive Detector) for small AC voltage measurement. When oscillator output voltage has asymmetric (the period of positive and negative cycle) wave form, it will generate measurement error. This is the reason of BPF. Q of the BPF is 10. When you use external oscillator, you should care to the same thing.
Some transistors use 270[Hz] for measurement frequency. **Figure 9** is BPF for 270[Hz] (Q=10).

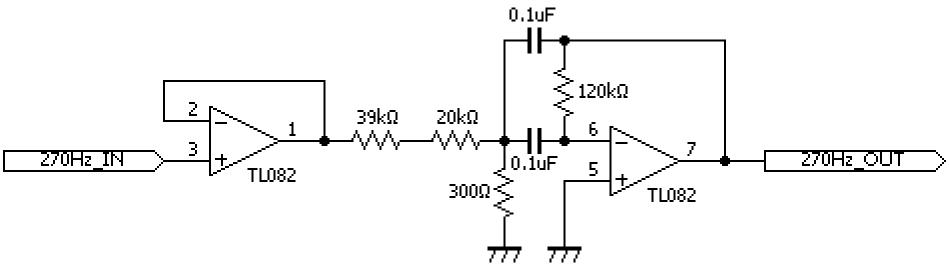


Figure 9. 270[Hz] BPF

Output of BPF go into A301-2 (buffer amplifier) through J505 (EXTERNAL OSC). A301-2 output go into 3 order HPF (High Pass Filter and cut-off frequency is 200[Hz]) that consist of A301-3. The reason of HPF is AC power line noise rejection. When you use external oscillator, output signal contain some AC power line noise. AC power line noise become jitter at PSD and jitter generate measurement error. This is the reason of HPF.

A301-3 (HPF) output is go into A302-3 for getting inverted signal and the output signals apply to OSC1 OSC2, OSC3 and OSC4 (**Figure 1**) through S502-3 and S503-4. A302-3 inverted signal use for take phase matching between oscillator output and dV_{CE}/dI_E.
A301-3 output go into AC voltage measurement circuit (**Figure 3**) through 1/1000 of voltage divider (R314 to R317). The purpose of the voltage divider is to measure oscillator output with the same measurement circuit for DUT. Measurement circuit has 1000[V/V] of voltage amplifier (A304) because of small voltage, so 1[V] of oscillator output voltage is too big for this amplifier.

A303 is input amplifier of AC voltage measurement circuit. This is complex circuit because using PSD technique. The major reason of PSD is small AC voltage measurement. For example, in dV_{BE}/dV_{CE} measurement, we have to measure micro volt level of small signal. Another reason is, this test method needs phase information in the calculation. PSD is good solution for these requirements. PSD output is DC voltage, so you can use regular multi-meter even analog multi-tester.

PSD operation and signal flow is the following:
Oscillator output signal go to DUT (dV_{CE} and dI_E) and this output signal also go into the phase shifter (**Figure 4**). Input/Output signal of phase shifter is, input is sine wave voltage and output is square wave current. The phase shift value is adjusted by VR401. You can get ±90º of phase shift with continuity and lineally.
Output of phase shift is square wave current that generate by TR403. TR302 is driven by this square wave current. TR302 generates square wave voltage for IC301.
IC301 is analog switch (multiplexer) and ON/OFF determine by TR302 output voltage level (H/L). The connection of **Figure 3** is,

- When TR302 output = H, IC301 Pin 13 signal has no phase inversion.

- When TR302 output = L, IC301 Pin 13 signal has phase inversion.

The signal source of TR302 is phase shifted oscillator output and the signal source of IC301 input signal is oscillator output via DUT or voltage divider. The difference of both signals is phase. **Figure 10** shows oscillator output and IC301 Pin 13 (refer to Pin 3) signal when 0º of phase difference. The operation of IC301 is PSD.

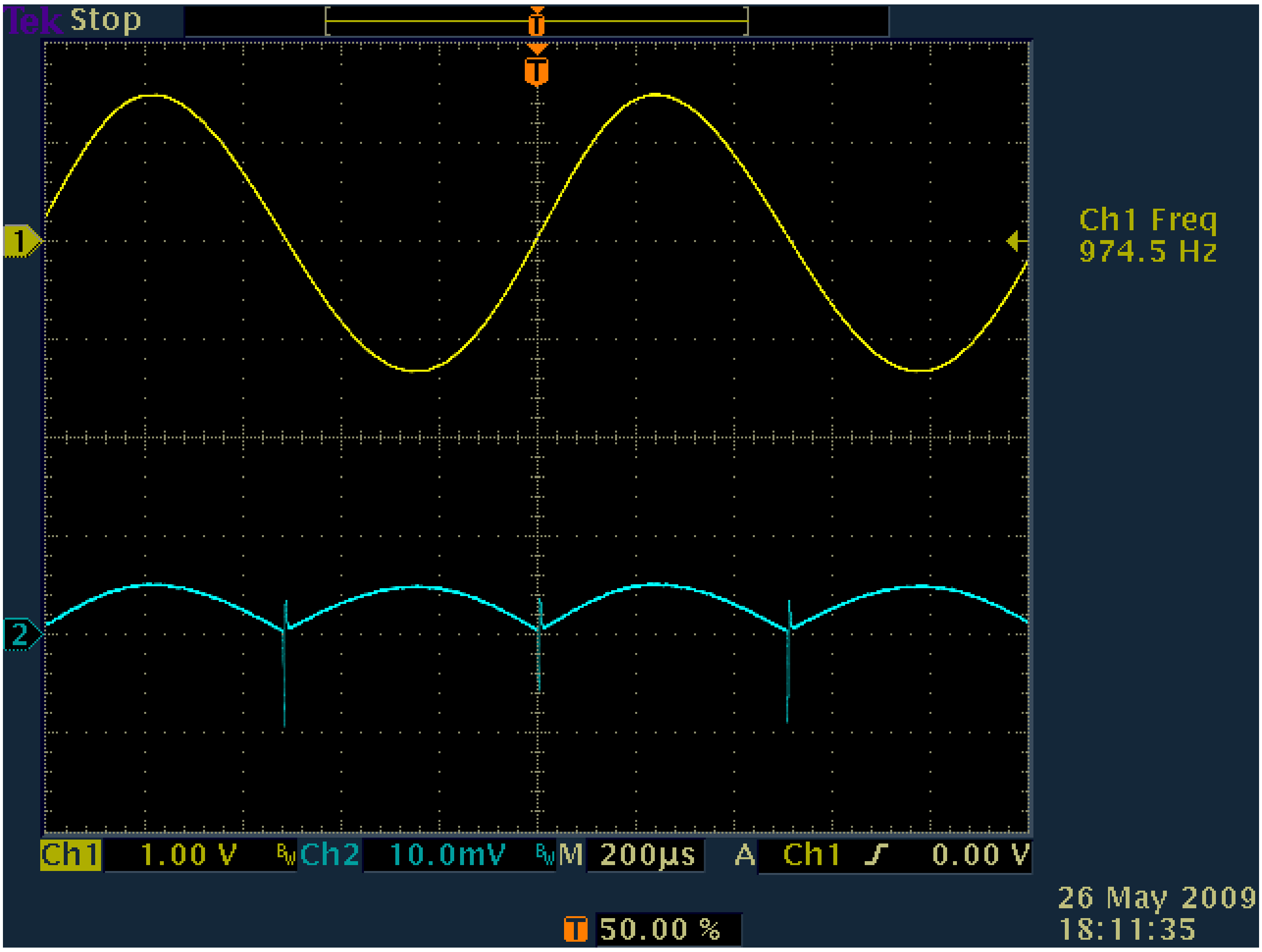


Figure 10. Oscillator output (Upper) and PSD output(Lower)

In the PSD operation, synchronized input signal convert to DC voltage. Unsynchronized signals (even DC offset voltage) convert to AC voltage. LPF that consist of R337 and C335 (cut-off frequency is 3.4[Hz]) extract DC signal. When use PSD, we can detect micro-volt AC signal easily.

The PSD output is the averaged AC voltage, so the amplitude at LPF output (DC voltage) gives multiplication $2/\pi$ (~0.637) and AC peak voltage (**Figure 10** is not PSD input/output, so you cannot calculate from the picture).

You may have question about "Transformer (T301) must effect to the accuracy. Is it OK?" The answer is OK. The reason is the following:

If we need absolute value, transformer effect to the accuracy. However, this test method doesn't use absolute value. This test method uses relative value. h_{fe} is one of example, h_{fe} is the ratio of I_C and I_B (dI_C/dI_B), it doesn't need absolute value. Other parameters has the same situation.

PSD convert from AC voltage to DC voltage, DC voltage is small voltage also. So DC voltage go into 1000[V/V] (or 100[V/V]) of amplifier (A304). When you choose x1000 (=1000[V/V]) with S505, and select AC with S504, A304 output voltage will appear J501 (OUTPUT).

You can choose x100 (=100[V/V]) with S505. When A304 saturated, x100 is useful. However you can use x1000 for the forward characteristics measurement for almost all transistors.

This is signal flow for four parameters measurement (dI_{B1}/dI_{E1}, dV_{BE1}/dI_{E1}, dI_{B2}/dV_{CE2}, dV_{BE2}/dV_{CE2}) in **Figure 7 a/b**.

DC Measurement

In DC measurement, S502 set to GND or OSC position for cut the oscillator to DUT line. S501 use for NPN/PNP selection. S504 set to DC. S503 use for operating condition setting or DC characteristics measurement.

Each position of S503 are the following:

G2S (S503) mean V_{G2S} (Voltage between Gate 2 and Source for dual gate FETs) and **Figure 6** is V_{G2S} generator. G2S use for operating condition setting. V_{G2S} appear J501. You can set V_{G2S} with no DUT.

Figure 6 is little complex circuit, because use IC201 for voltage reference. VR501 is linear taper potentiometer and when set potentiometer knob to the center, V_{G2S}=0[V]. The range of V_{G2S} is -4 to +5[V]. This number covers almost all MOSFETs but JFETs (ex. 3SK28).

IE_MON (S503) is an abbreviation of "Emitter current (or Source current) monitor" However this is not current output. A201-1 output voltage (referenced to minus power supply line) appears on J501 (OUTPUT). The voltage range of IE_MON is 0.1 to 20[V] and this voltage correspond to 0.1 to 20[mA]. You can set Emitter current with no DUT.

VCE_MON (S503) is an abbreviation of "Collector - Emitter voltage monitor" However this is not the voltage between Collector - Emitter. A201-2 output voltage (referenced to minus power supply line) appears on J501 (OUTPUT) and the voltage range is 0 to 20[V] that correspond to 0 to 20[V] of V_{CE}. You can set V_{CE} with no DUT.

VBE (S503) is DUT Base - Emitter voltage and this voltage appear on J501 (OUTPUT) through 1[kΩ] of buffering resistor (**Figure 1**). When you choose voltmeter, you should care input resistance of the voltmeter.

IB (S503) is the voltage drop at R110 (for NPN) or R138 (for PNP) and Base current of the DUT. Voltage meter input resistance should have much higher resistance than 10[kΩ] (R110 and R138).

Instance of the Measurement

Common Items

Power switch is S505. This switch turn ON/OFF for all of circuits including measurement circuit. From this, oscillator and amplifiers will have warm-up drift right after S505 turn ON. So you should change the DUT quickly and take warm-up time. When add a switch for DUT, you should care stray capacitance of the wires because it is the factor of the measurement error. In transistor measurement, 1[pF] of small capacitance effect to measurement accuracy.

When you use external oscillator, oscillator connect to J505. Oscillator that has output level adjuster is must be useful. Oscillator wire connect to S505 (Power switch), so you don't need oscillator ON/OFF when power ON/OFF.

S502 set to GND except continuously measurement of the specific parameter. GND position doesn't apply AC signal to the DUT.

S505 set to x1000 (=1000[V/V]).

DC voltmeter connect to J501. You can use Digital or Analog DC voltmeters. However you should care input resistance. In Base current measurement, R110 or R138 (10[kΩ]) use for current sense, so voltmeter should have ≥1[MΩ] of input resistance. Some Analog voltmeters doesn't have this condition. If you don't measure DC Base current, you can use almost all DC voltmeters.

You can adjust Collector - Emitter voltage (V_{CE}) and Emitter current (I_E) with no DUT.

V_{CE} is adjusted by VR203. S503 set to VCE_MON and S504 set to DC, V_{CE} appear on DC voltmeter that connected J501. When you set V_{CE}=10[V], adjust VR203 to 10[V] of the DC voltmeter reading. In **Figure 7**, AC voltage (dV_{CE2}) superimpose on DC voltage (V_{CE2}), the amplitude of $dV_{CE\,2}$ is 0.25[V] of fixed value and this amplitude depend on oscillator output voltage.

I_E is adjusted by VR202. S503 select IE_MON and S504 select DC, I_E corresponding voltage appear on DC voltmeter that connected J501. When you set I_E=10[mA], adjust VR202 to 10[V] of the DC voltmeter reading. This mean, convert [V] to [mA] directory. In **Figure 7**, AC current ($dI_{E\,1}$) superimpose on DC current (I_{E1}), the amplitude of $dI_{E\,1}$ is 20[μA] of fixed value and this amplitude depend on oscillator output voltage.

V_{G2S} (Voltage for Second Gate -Source of Dual Gate FET) is adjusted by VR601. S503 set to G2S and S504 set to DC, V_{G2S} appear on DC voltmeter that connected J501. When you set V_{CE}=-1[V], adjust VR601 to -1[V] of the DC voltmeter reading.

Above explanations are adjustment before measurement. When you change the DUT, I recommend S506 (Power switch) turn OFF during change. Because this transistor meter use operational amplifier for DUT driving. When No DUT, operational amplifier is saturating state. When DUT connect in this state, there is possibility of make some stress to the DUT.

In AC measurement, you can measure Offset voltage and Oscillation output voltage even if No DUT and internal/external oscillator.

Offset voltage is AC measurement circuit of that and it has frequency dependency. Switching noise in the PSD may become the offset voltage. However there is No dependency to the phase adjuster of the PSD (position of VR401). Offset voltage measurement perform with S502 set to GND, S504 set to AC and read DC voltmeter that connected to J501. The offset voltage is the reading of the voltmeter divides by A304 voltage amplification. You can select the A304 voltage amplification (100[V/V] or 1000[V/V]) with S505.

Oscillator output voltage measurement perform with S502 set to OSC, S504 set to AC and read DC voltmeter that connected to J501. This measurement requires phase adjustment (VR401) in the PSD. Seek the positive peak voltage with VR401 and the position (phase angle) of VR401 is 0º (reference of the phase). The reading of DC voltmeter divides by A304 voltage amplification and subtract offset voltage from this number. This is oscillator output voltage. You can select the A304 voltage amplification (100[V/V] or 1000[V/V]) with S505.

BJT Measurement

Here is an instance of 2SC1815GR (NPN-BJT) measurement.

From the datasheet, manufacture use 270[Hz] for the AC measurement. Transistor meter has 980[Hz] oscillator only, so use an external oscillator. When distortion of the oscillator is not good, use BPF (**Figure 9**).

Set V_{CE}=10[V] and I_E=2[mA] for operating condition of the DUT.

Turn ON S506 (Power switch). S501 set to NPN because 2SC1815 is NPN-BJT. S503 set to VBE, S504 set to DC and check V_{BE} with DC voltmeter that connected to J501. When confirm ~0.7[V], feedback loop that including DUT may work normally. At this point, V_{BE} drift with heat itself, if you measure V_{BE}, you should take warm-up time. AC parameter doesn't have big drift, so procedure of the measurement is AC first and DC.

S504 set to AC and S505 set to x1000, in this setting, AC parameters measurement performed like the following:

- S502 set to GND and record DC voltmeter reading. It was +26[mV].
- S502 set to OSC and seek positive peak voltage with VR401. Record DC voltmeter reading and phase from VR401 position. It was +1.02[V] and 0º.
- S502 set to dVBE/dIE position and seek positive peak voltage with VR401. Record DC voltmeter reading and phase from VR401 position. It was +286[mV] and 0º.
- S502 set to dIB/dIE position and seek positive peak voltage with VR401. Record DC voltmeter reading and phase from VR401 position. It was +919[mV] and 0º
- S502 set to dVBE/dIVCE position and seek Negative peak voltage with VR401. Record DC voltmeter reading and phase from VR401 position. It was -7[mV] and -18º This number is negative number because of Base width modulation (Early effect).
- S502 set to dIBdIVCE position and seek Negative peak voltage with VR401. Record DC voltmeter reading and phase from VR401 position. It was -25[mV] and +12º This number is negative number because of Base width modulation (Early effect).

From recorded numbers, calculate normalized numbers of dVBE/dIE, dIB/dIE, dVBE/dVCE and dIB/dVCE. The calculation uses complex number. Using spreadsheet is one of useful calculation method.

At first, get complex number (Re and Im) from recorded voltage (A[V]) and phase (P[º]). The expression is,

$$Re = A \times \cos\left(\frac{\pi}{180} \times P\right) \quad , \quad Im = A \times \sin\left(\frac{\pi}{180} \times P\right)$$

Spreadsheet use radian ([rad]) for a trigonometric function. Above expressions includes this background. The expression of the spreadsheet is,

=COMPLEX(A*COS(PI()/180*P), A*SIN(PI()/180*P))

When input COMPLEX (Re, Im) to the spreadsheet cell, spreadsheet memorize complex number in to the one cell. Useful functions that like COMPLEX are the following:

IMSUM, IMSUB, IMPRODUCT, IMDIV, IMABS

These are four rules of arithmetic and getting absolute number from complex number. Please get more information from HELP in the spreadsheet.

Let's start calculation from above basic knowledge. On the computer screen shows spreadsheet like **Figure 11**.

	A	B	C	D	E
1	Vos@x1000	2.60E-02			
2	OSC	1.02E+00	0.00E+00	0.994	9.94E-01
3	dVBE/dIE	2.86E-01	0.00E+00	13.0784708	2.60E-04
4	dIB/dIE	9.19E-01	0.00E+00	4.4919517	8.93E-08
5	dVBE/dVCE	-7.00E-03	-1.80E+01	-1.2629724	3.30E-05
6	dIB/dVCE	-2.50E-02	1.20E+01	-2.0074659	5.10E-09

Figure 11. Indication of the Spreadsheet

Column A is title for rows. Column B is the measured voltage and column C is measured phase. Column D is normalized complex number of dVBE/dIE, dIB/dIE, dVBE/dVCE, dIB/dVCE and these number calculated from column B and C. Column E is absolute number of column D.

Column D is normalized number ("/dIE" normalized with 1[A] and "/dVCE" normalized with 1[V]). These normalized number are useful for the application and this is the reason of why normalize.

Before start explanation for each cell, it need cell addressing rule. Cell addressing rule use the same as the spreadsheet one. In **Figure 11**, the cell that indicates "Vos@x1000" is A1. Next right side cell that indicates "2.60E-2" is B1. The order is Column - Row.

D2 input data is the following:

=IMPRODUCT(IMDIV(COMPLEX((B2-B1)*COS(PI()/180*C2), (B2-B1)*SIN(PI()/180*C2)), COMPLEX(1000, 0)), COMPLEX(1000, 0))

This data come from the following expression:

$$Re=\frac{(B2-B1)\times\cos(\frac{\pi}{180}\times C2)}{1000}\times 1000\ ,\quad Im=\frac{(B2-B1)\times\sin(\frac{\pi}{180}\times C2)}{1000}\times 1000$$

Meaning of D2 is A301-3 and A302-3 output voltage (Oscillator output voltage).

The part of (B2-B1) is, remove offset voltage (B1) from measured voltage (B2).

Denominator of the fraction is A304 voltage amplification (1000[V/V]).

The multiplier of the fraction is reciprocal number of the 1/1000[V/V] of voltage divider (that consist of R314 to R317).

E2 input data is the following:

=IMABS(D2)

Meaning of E2 is absolute value of D2. **Figure 11** E2 indicates 9.94E-1. Meaning of this is voltage amplitude at A301-3 and A302-3 (oscillator output voltage) is 994[mV].

D3 input data is the following:

=IMDIV(IMDIV(COMPLEX((B3-B1)*COS(PI()/180*(C3-C2)), (B3-B1)*SIN(PI()/180*(C3-C2))), COMPLEX(1000, 0)), IMDIV(D2, COMPLEX(50000, 0)))

This data come from the following expression:

$$Re=\frac{\dfrac{(B3-B1)\times\cos(\frac{\pi}{180}\times(C3-C2))}{1000}}{\dfrac{D2}{50E3}}, \quad Im=\frac{\dfrac{(B3-B1)\times\sin(\frac{\pi}{180}\times(C3-C2))}{1000}}{\dfrac{D2}{50E3}}$$

Meaning of D3 is dVBE/dIE when dIE=1[A] (normalized value).
The part of (B3-B1) is, remove B1 (offset voltage) from B3 (measured voltage).
The part of (C3-C2) is, remove C2 (phase of the oscillator) from C3 (measured phase).
"1000" of denominator is A304 voltage amplification (1000[V/V]).
"D2/50E3" is dIE when B3 measured, it get from oscillator output voltage (D2) divides by R104||R105 or R142||143 (50[kΩ]).

E3 input data is the following:

=IMABS(IMPRODUCT(D3, IMDIV(D2, COMPLEX(50000, 0))))

This data come from the following expression:

$$|dV_{BE}|=\left|D3\times\frac{D2}{50E3}\right|$$

Meaning of E3 is dVBE/dIE of the DUT when B3 measured. And this is absolute value. **Figure 11** E3 indicates 2.60E-4. Meaning of this is 260[μV] of dVBE when ~20[μA] of dIE in **Figure 7 a**.

D4 input data is the following:

=IMDIV(IMDIV(COMPLEX((B4-B1)/10000*COS(PI()/180*(C4-C2)), (B4-B1)/10000*SIN(PI()/180*(C4-C2))), COMPLEX(1000, 0)), IMDIV(D2, COMPLEX(50000, 0)))

This data come from the following expression:

$$Re=\frac{\dfrac{\frac{B4-B1}{10E3}\times\cos(\frac{\pi}{180}\times(C4-C2))}{1000}}{\dfrac{D2}{50E3}}, \quad Im=\frac{\dfrac{\frac{B4-B1}{10E3}\times\sin(\frac{\pi}{180}\times(C4-C2))}{1000}}{\dfrac{D2}{50E3}}$$

Meaning of D4 is dIB/dIE when dIE=1[A] (normalized value).

The part of (B4-B1) is, remove B1 (offset voltage) from B4 (measured voltage).
This number divides by 10E3, this denominator is resistance of R110 or R138 (10[kΩ]).
The part of (C4-C2) is, removeC2 (phase of the oscillator) from C4 (measured phase).
"1000" of denominator is A304 voltage amplification (1000[V/V]).
"D2/50E3" is dIE when B4 measured, it get from oscillator output voltage (D2) divides by R104||R105 or R142||143 (50[kΩ]).

E4 input data is the following:

=IMABS(IMPRODUCT(D4, IMDIV(D2, COMPLEX(50000, 0))))

This data come from the following expression:

$$|dI_B| = \left| D4 \times \frac{D2}{50E3} \right|$$

Meaning of E4 is dIB/dIE of the DUT when B4 measured. And this is absolute value. **Figure 11** E4 indicates 8.93E-8. Meaning of this is 89.3[nA] of dIB when ~20[μA] of dIE in **Figure 7 a**.

D5 input data is the following:

=IMDIV(IMDIV(COMPLEX((B5-B1)*COS(PI()/180*(C5-C2)), (B5-B1)*SIN(PI()/180*(C5-C2))), COMPLEX(1000, 0)), IMPRODUCT(D2, COMPLEX(0.25, 0)))

This data come from the following expression:

$$Re = \frac{\dfrac{(B5-B1) \times \cos(\frac{\pi}{180} \times (C5-C2))}{1000}}{D2 \times 0.25}, \quad Im = \frac{\dfrac{(B5-B1) \times \sin(\frac{\pi}{180} \times (C5-C2))}{1000}}{D2 \times 0.25}$$

Meaning of D5 is dVBE/dVCE when dVCE=1[V] (normalized value).
The part of (B5-B1) is, remove B1 (offset voltage) from B5 (measured voltage).
The part of (C5-C2) is, remove C2 (phase of the oscillator) from C5 (measured phase).
"1000" of denominator is A304 voltage amplification (1000[V/V]).
"D2*0.25" is dVCE when B5 measured, it get from multiply oscillator output voltage (D2) and 0.25 (R115/R114 or R134/R13) together.

E5 input data is the following:

=IMABS(IMPRODUCT(D5, IMPRODUCT(D2, COMPLEX(0.25, 0))))

This data come from the following expression:

$$|dV_{CE}| = |D5 \times (D2 \times 0.25)|$$

Meaning of E5 is dVBE/dVCE of the DUT when B5 measured. And this is absolute value.

Figure 11 E5 indicates 3.30E-5. Meaning of this is 33[µV] of dVBE when ~250[mV] of dVCE in **Figure 7 b.** E5 doesn't have sign because of absolute value. However E5 should has minus sign because of Base width modulation (Early effect).

D6 input data is the following:

=IMDIV(IMDIV(COMPLEX((B6-B1)/10000*COS(PI()/180*(C6-C2)), (B6-B1)/10000*SIN(PI()/180*(C6-C2))), COMPLEX(1000, 0)), IMPRODUCT(D2, COMPLEX(0.25, 0)))

This data come from the following expression:

$$Re=\frac{\dfrac{\dfrac{B6-B1}{10E3}\times\cos\left(\dfrac{\pi}{180}\times(C6-C2)\right)}{1000}}{D2\times 0.25}, \quad Im=\frac{\dfrac{\dfrac{B6-B1}{10E3}\times\sin\left(\dfrac{\pi}{180}\times(C6-C2)\right)}{1000}}{D2\times 0.25}$$

Meaning of D6 is dIB/dVCE when dVCE=1[V] (normalized value).
The part of (B6-B1) is, remove B1 (offset voltage) from B6 (measured voltage).
This number divides by 10E3, this denominator is resistance of R110 or R138 (10[kΩ]).
The part of (C6-C2) is, remove C2 (phase of the oscillator) from C6 (measured phase).
"1000" of denominator is A304 voltage amplification (1000[V/V]).
"D2*0.25" is dVCE when B6 measured, oscillator output voltage (D2) convert to 1/4 (=0.25) of amplitude at A101-1 and A101-4.

E6 input data is the following:

=IMABS(IMPRODUCT(D6, IMPRODUCT(D2, COMPLEX(0.25, 0))))

This data come from the following expression:

$$|dI_B|=|D6\times(D2\times 0.25)|$$

Meaning of E6 is dIB/dVCE of the DUT when B6 measured. And this is absolute value. **Figure 11** E6 indicates 5.10E-9. Meaning of this is 5.1[nA] of dIB when ~250[mV] of dVCE in **Figure 7 b**. E6 doesn't have sign because of absolute value. However E6 should has minus sign because of Base width modulation (Early effect).

The above explanation is BJT AC measurement.
BJT DC measurement is the following:

2SC1815GR use for DUT. S501 turn to NPN because 2SC1815GR is NPN-BJT. S502 select GND or OSC position and S504 turn to DC. Under this condition, you can measure V_{BE} and I_B with S503 selection.

V_{BE} DC measurement, S503 set to VBE. Read DC voltmeter that connected J501 (OUTPUT) and this reading is the V_{BE}. The reference voltage (=0[V]) of V_{BE} measurement is Emitter voltage. So NPN-BJT takes positive number and PNP-BJT takes negative number.

In case of 2SC1815GR V_{BE} DC measurement, it was +0.658[V] at V_{CE}=+10[V] and I_E=-2[mA].

In V_{BE} measurement, you should care the self-heating. V_{BE} is in proportion to logarithmic Collector current (I_C). I_C and I_E has $I_E=I_C*(1+1/h_{FE})$ of relation and the case of $1 \ll h_{FE}$, $I_E \simeq I_C$. From the logarithmic characteristic, dV_{BE}/dI_C became smaller at larger I_C. The other hand, V_{BE} decrease when temperature increasing.

From these characteristics, 2SC1815GR V_{BE} increased at I_C<10[mA] region, V_{BE} decreased at I_C>10[mA] region. So in the V_{BE} DC measurement, you should care self-heating.

When you need accurate V_{BE}, there is "Pulsed measuring technique" Unfortunately this transistor meter doesn't have this function. However you can confirm the positive relation between dV_{BE} and dI_C with dVBE/dIE in AC measurement at I_C>10[mA] region, because self-heating cannot follow 270 to 1000[Hz] of oscillation frequency.

I_B DC measurement, S503 set to IB. Read DC voltmeter that connected J501 (OUTPUT). I_B is, reading number divides by resistance of R110 or R138 (10[kΩ]). The sign of the I_B is, plus direction is current that flow into the transistor, minus direction is current that flow out from the transistor. I_B of NPN or PNP BJT has the same rule even I_C and I_E. From this rule, NPN-BJT I_B takes plus sign and NPN-BJT I_B takes plus sign.

In case of 2SC1815GR V_{BE} DC measurement, DC voltmeter reading was +91.5[mV] at V_{CE}=+10[V] and I_E=-2[mA]. h_{FE} (DC current gain) is

$$h_{FE}=\frac{I_C}{I_B}=\frac{-I_E-I_B}{I_B}=\frac{-I_E}{I_B}-1=\frac{-(-2\text{E-3})}{9.15\text{E-6}}-1=219 \quad \text{[A/A]}$$

From **Figure 11**, h_{fe} (AC current gain @ 270[Hz]) is, subtract 1 from reciprocal number of cell D4 (complex number) in **Figure 11**. The result is 222[A/A]. This number is almost the same number to DC measurement. Both of results should agree.

The other BJT DC measurement, there is I_C measurement of the V_{CE} dependency (I_B=constant) for example. This transistor meter doesn't have current source for Base of the BJT. However we can measure this with the following procedure:

Set specific V_{CE} and S503 set to IB, read DC voltmeter that connected J501 (I_B measurement). Adjust VR202 (I_E) for getting specific I_B. After that, S503 set to IE and read DC voltmeter (I_E measurement). I_C get from $-I_E-I_B$ of calculation.

This is a little complex procedure, however you can get the value under the specific condition.

JFET and MOSFET measurement

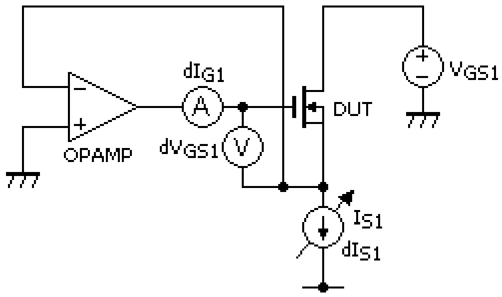


Figure 12 a. Test for Source Current shaking

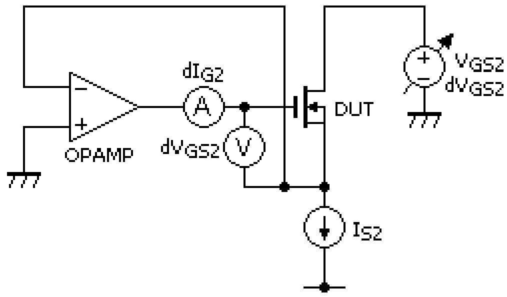


Figure 12 b. Test for Drain-Source Voltage shaking

Figure 12 a/b are the connection for (Single Gate) FET measurement. These circuits are the same circuits as **Figure 7 a/b** except DUT. **Figure 12** uses MOSFET for the DUT, you can use JFETs with the same idea.

Gate leakage current measurement is difficult to perform with this transistor meter because it is too small (<1[nA] for example). In AC measurement, you can measure some Gate current that caused by capacitance for example.

Other measurements (including test procedure and calculation), these are the same as BJT. Please refer to BJT.

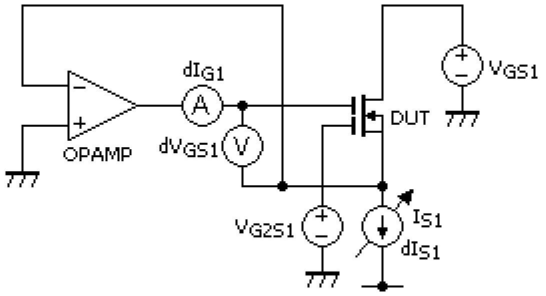
I_{DSS} is one of FET DC characteristic (I_D when V_{GS}=0[V]). This measurement perform with the following procedure:

S502 set to GND or OSC, S504 set to VBE and DC voltmeter connect to J501. Apply specific V_{DS}. In this condition, adjust VR202 (I_S, Source current) for getting 0[V] of the DC voltmeter. After that, S503 set to IE_MON and read the DC voltmeter. This voltage indicate [mA] of I_S. In case of FET, we can assume I_D=I_S (when we can neglect Gate leakage current). From this you can get I_{DSS}.

This test procedure also use for V_{GS}-I_D characteristic measurement.

Here is an instance of I_{DSS} measurement for 2SK364BL (N-JFET). S501 set to NPN, S504 set to DC, S503 set to VCE_MON and DC voltmeter connect to J501 (OUTPUT). Adjust VR203 to +10[V] of DC voltmeter reading (V_{DS}=+10[V]). S503 set to VBE and adjust VR202 to 0[V] of DC voltmeter reading. S503 set to IE_MON and read DC voltmeter. It was +6.86[V], so I_{DSS} is 6.86[mA].

Dual Gate FET Measurement



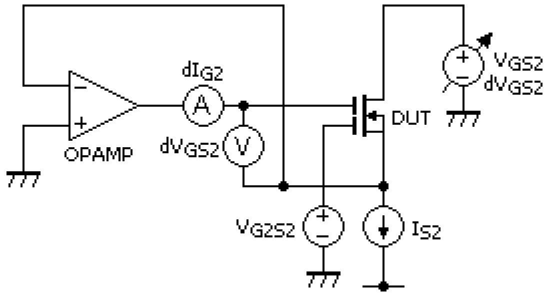


Figure 13 a. Test for Source Current shaking

Figure 13 b. Test for Drain-Source Voltage shaking

Figure 13 a/b are the connection for Dual Gate FET measurement. J601 (G2 DRIVE) is V_{G2S1} or V_{G2S2} in **Figure 13**. Manufacture decides Gate 1/Gate2 in the datasheet. However you can swap G1 and G2 in the measurement with this meter.

This transistor meter correspond to N channel FET only and G2 voltage range is -4 to +5[V] (refer to the Source voltage).

Points of the Building

Important point is coupling oscillating signal and Base (or Gate) wire with stray capacitance. One of example is Collector wire. AC voltage superimpose on the DC voltage in AC measurement. So shield cable use for this wire. Another example is Phase Shifter (**Figure 4**). There is over 20[V] of AC voltage (TR401 and TR402 collector voltage), so this circuit should shield. In **Figure 3**, there is an oscillator and measurement circuit together. However, oscillator and measurement circuit should have shield.

When consider degree of the shield, one of example is C_{ob} (Capacitance between Collector and Base) of BJT. When estimate C_{ob}=1[pF] and dV_{CE} in **Figure 7 b** is 0.25[V]. In this condition, Base current that caused by C_{ob} is

$$I_b = \frac{V}{Z_C} = \frac{1}{\frac{1}{2\pi f C}} = 1 \times 2\pi \times 1E3 \times 1E\text{-}12 = 6.28 \quad \text{[nA]}$$

This transistor meter is able to detect this value of the current at smaller Collector current. From this, when exist this value of the current that caused by stray capacitance, it become measurement error. So shield is one of key factor.

At the negative feedback loop including DUT, wires for feedback loop should not use long wire. Operational amplifier works with unity gain amplifier, so should not use shield cable because shield cable is capacitive load of the operational amplifier and there is possibility of the oscillation. From this background, minimized length wire is the solution. In my case, operational amplifier positioned near terminals and operational amplifier including peripheral components mounted of the separated board.

Wiring around the rotary switch also need some care for stray capacitance. These wiring tie with minimized length of wire. Assignment of switch terminals is key factor of this.

Resistors that no mention of the tolerance in circuit diagrams, you can use 5[%] carbon resistor. Some resistors specified 1[%] tolerance in the circuit diagram, metal film resistor is fine.

Capacitors that use for oscillator or filters are 5[%] of tolerance film capacitors. C403, there is 2[mA] of current flow. Some manufactures doesn't recommend any current flow because current flow make heating up with ESR and it's make some damage to the life-time. I recommend to check current and life-time chart, some manufactures issue this data.

VR201 (Reference voltage adjuster) and VR301 (Oscillation level adjuster) are trimming potentiometers that has 1 turn (~300°).

VR302 (A304 offset voltage adjuster) is 10 turns of trimming potentiometer.

VR401 (Phase adjuster) and VR601 (V_{G2S} adjuster) are linear taper potentiometers.

VR202 (I_E adjuster) and VR203 (V_{CE} adjuster) are logarithmic taper potentiometers. 10 turns linear taper potentiometers are good choice also.

Adjustment

At adjustment process, perform 15 minutes of warm-up at first.

IC201 output voltage adjust with VR201. VR201 adjust to 5.00[V] ± 10[mV] at between IC201 output and -15[V] power supply line. This voltage use for V_{CE}, I_E and V_{G2S} voltage reference.

VR302 (A304 offset) adjust with the following steps. S502 set to GND, S504 set to AC and DC voltmeter connect to J501. VR302 adjust to 0[V] at DC voltmeter. And this offset voltage has dependency of the frequency.

VR301 (Oscillator output) adjust with the following steps. S502 set to OSC, S504 set to AC and DC voltmeter connect to J501. Seek peak voltage with VR401 (Phase adjustor) and VR401 position should be around the center of the revolution. VR301 adjust to 1[V] at DC voltmeter.

Filter doesn't need adjustment when you use 5[%] of tolerance resistors and capacitors.

Oscillator adjustment has a little complex procedure, so it explain at next section.

Evaluation of the transistor meter after the building, take data and compare to datasheet is one of possible method. When you choose samples, I recommend to include FET that has small C_{rss} (Drain-Gate capacitance). You can check undesirable coupling with dIB/dVCE (S502 position) measurement. The phenomenon of undesirable coupling is 90° of Gate current.

Oscillator Adjustment

TR301 oscillator adjustment need an oscilloscope. I recommend to perform preliminary experiment on the bread-board. And use the same components to the same location in the circuit.

The purpose of the preliminary experiment is getting stability and low distortion. Many books handle the phase shift oscillator, so it looks easy. But it is a little complex. For example, when TR301 has too larger gain than oscillation theory, oscillator output will have distortion. And oscillator works another oscillation mode sometimes.

This explanation is my experience. I believe you can get sense for adjustment of the oscillator.

VR301 (2[kΩ]) and R305 (300[Ω]) of series circuit is "my case" When remove R305 (0[Ω]), voltage gain go down and oscillation became unstable. WhenVR301 change to 5[kΩ], oscillator output had distortion from large voltage gain. The exact value of VR301 (2[kΩ]) was 1.85[kΩ]. Distortion occurred when R305 change to 1[kΩ]. In my case, appropriate value of R305 was 150[Ω] to 470[Ω]. From this background, I fixed 300[Ω].

C305 doesn't appear in the books. When remove this capacitor, oscillator worked another oscillation mode. Oscillation frequency was not desirable frequency.

I got stability and low distortion from above experiment. Next step is oscillation frequency adjustment.

I chose 980[Hz] for oscillation frequency because avoid harmonics of AC power line frequency (50 or 60[Hz]).

Capacitor that use phase shift network, it should has good stability. I use polypropylene film capacitors. Oscillation frequency shift with slight value change of the components.

For example, phase shift network consist of 6 CRs, when swap components within 6 CRs, oscillation frequency had unacceptable change.

After experiment and soldered all of components on the board, I used 150[pF] of capacitor for frequency adjustment. After the soldering, oscillator has good stability.

The following expression is oscillation frequency for this oscillator in the textbook.

$$f_{OSC} = \frac{1}{2\pi\sqrt{6}CR}$$

C305 make some effect to oscillation frequency with output impedance, so actual oscillation frequency is lower frequency from that expression.

Finally

This transistor meter is my first try. I built some test equipments for linear ICs or mixed signal ICs, however I don't have opportunity to build transistor tester.

There is a feedback. I crammed these circuit into the small case. As the result, I got difficult to remove undesirable coupling. When I improve this, I have to reconsider the shielding, board separating and mounting in the case. I recommend to use small metal cases for separated board and all of cases mount into the large metal case like high frequency measurement equipments.

The circuit, I'm satisfied it because my purpose of this meter is "Get practical and necessity performance with easy circuit"

This meter uses current-mirror and some transistor circuit, I think, if I have this meter when I evaluate each circuit on the bread-board, I could finish the evaluation more quickly.

Frequency rage is 270[Hz] to 1000[Hz] of narrow band width. The restriction came from phase shifter (**Figure 4**) for the major factor. When cover wide range, it needs a range selector switch. This meter designed within no range selector.

Applicable calculation (ex. h-parameters) will publish another document. In this project, I researched semiconductor physics. When I have opportunity of publishing, I hope to explain relation between semiconductor physics and h-parameters for example. It must be help when you consider the SPICE modeling.

In high frequency transistor measurement with this meter, it needs prevention technique of the oscillation. This technique will include in the another document.

August/15/2009