Semiconductor Circuit Design

for a.f. and d.c.
amplification and switching

J. WATSON
B.Sc., S.M., Ph.D., A.M.I.E.E.
University of Wales, Swansea

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PREFACE

There are on the market at present several general texts that cover the fundamental tenets of transistor circuit analysis and design, and deal with an extremely wide range of topics including high-frequency networks and switching as applied to logic circuits. The present book, however, concentrates on the amplification and switching of audio frequency and direct currents, and offers a treatment in somewhat greater depth than would be possible in a more widely based volume. It also includes introductory discussions on semiconductor devices other than bipolar transistors, and particular emphasis is placed on the photoelectric family, whose usefulness in general circuit design has not yet been fully appreciated. The field effect transistor is also included, for it is rapidly gaining in popularity as designers begin to recognize its undoubted superiority over the bipolar transistor in many applications, and as cheaper and more versatile types become available.

Throughout the text an effort has been made to stress the importance of design rather than analysis, and in that this is necessarily something of an art, it is hoped that an excessively academic treatment has been avoided.

The introductory chapters of the book are directed to some extent towards those who have experience in valve circuitry, and the inevitable analogies with the vacuum tube—and their limitations—have been placed in perspective. A preliminary explanation of the profound effects of temperature on transistors is given and the necessity for correct d.c. biasing is established. Chapter 3 presents some of the more important systems of characterization which relate to the incremental or small signal performance of transistors, and this is followed by a comprehensive discussion in Chapter 4 of the combination of biasing techniques and small signal concepts which leads to the design of simple amplifier stages. Chapter 5 follows with a discussion of multistage and feedback amplifiers, and concludes with notes on both stability and noise.

Chapter 6 extends the treatment of small signal amplifiers to cover high input impedance stages, and selective and d.c. amplifiers. It concludes with a section on power amplifiers and shows how it is possible to design for a 'perfect' transistor, then relax the specification to take account of practical limitations.

Chapter 7 is concerned with the use of transistors in both regenerative and non-regenerative switching circuits, and includes a discourse upon the more elementary forms of square-wave invertors.

The design of constant voltage and constant current power supplies is considered in Chapter 8. Whilst it is recognized that a wide range of constant voltage power packs is commercially available, this chapter is nevertheless included on the grounds that not only are special purpose supplies often needed, but the concepts behind such designs provide excellent examples of how many of the techniques appearing earlier in the book are brought together to form elementary electronic systems.

The remaining chapters are concerned with the more exotic semiconductor devices, and the book concludes with some examples of the incorporation of semiconductor circuits into complete systems. Here, the field of electro-optical instrumentation has been chosen because very many of the design examples given previously in the book are immediately relevant.

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J. WATSON

UNIVERSITY OF WALES
SWANSEA
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SYMBOLS AND ABBREVIATIONS

A	Voltage gain of a (hypothetical) perfect amplifier
A_{i}	Current gain of an amplifier
$A_{\mathrm{i(FB)}}$	Current gain of an amplifier when feedback is applied
A_{v}	Voltage gain of an amplifier
$A_{\mathrm{v(FB)}}$	Voltage gain of an amplifier when feedback is applied
A_{ov}	Voltage gain of an amplifier measured from the source end of an input resistor
$A_{\mathrm{ov(FB)}}$	As above, but when feedback is applied
$A_{\mathrm{v(diff)}}$	Differential voltage gain of a difference amplifier
$A_{\mathrm{v(CM)}}$	Common-mode voltage gain of a difference amplifier
a	The current gain parameter in a T-equivalent circuit ($\simeq\alpha$)

B	Feedback fraction
B	Magnetic flux density
B_{sat}	Magnetic flux density at saturation

C	Capacitance	
C_{C}	Coupling capacitor in cascaded stages	
C_{D}	Decoupling capacitor	
C_{E}	Capacitor connected across a resistor in an emitter lead	
C_{F}	Feedback capacitor	
C_{in}	Input capacitance	
C_{GD}	Gate-drain capacitance in a field-effect transistor	
C_{GS}	Gate-source capacitance in a field effect transistor	
CMR	Common-mode rejection ratio of a difference amplifier	
C_{tc}	Capacitance of the base-collector junction	Charge control parameters
C_{te}	Capacitance of the base-emitter junction when reverse biased	

D	Drain (of a field effect transistor)
D	Detectivity (of a photocell)
D^*	Specific detectivity
D_{l}	Illumination on a surface
D_{r}	Irradiation on a surface
dB	Decibel

E	Voltage, d.c. or r.m.s. a.c.
e	Voltage generated by a perfect voltage source

FET	Field-effect transistor
F_{T}	Gain-bandwidth product
f	Frequency

f_α or $f_{h_{\mathrm{fb}}}$	High-frequency cut-off point for CB mode
$f_\alpha{}'$ or $f_{h_{\mathrm{fe}}}$	High-frequency cut-off point for CE mode
f_1	Frequency at which modulus of h_{fe} becomes unity
f_{h}	High-frequency cut-off point for a circuit
f_{L}	Low-frequency cut-off point for a circuit
f_{m}	A frequency near the middle of a pass-band
f_λ	An ordinate of the visibility or lamprosity curve
G	Gate (of a field-effect transistor)
g_{m} or g_{fs}	Mutual conductance for a FET
H	Magnetizing force
H_{O}	Magnetizing force which ensures saturation
h	Planck's constant
h-parameters	See text p. 24
I	Current, d.c. or r.m.s. a.c.
I_{B}	Direct current in base lead
I_{C}	Direct current in collector lead
I_{CM}	Maximum safe collector current
$I_{\mathrm{C(m)}}$	Maximum current to which I_{C} can rise
I_{CS}	Collector current under conditions of saturation
I_{CBO} or I_{CO}	Collector-base leakage current with open-circuited emitter
I_{CEO}	Collector-emitter leakage current with open-circuited base
I_{E}	Direct current in emitter lead
I_{t}	Trigger current for a four-layer device
I_{Q}	Quiescent collector current
I_{Z}	Current through a Zener diode
i_{b}	Incremental base current
i_{c}	Incremental collector current
i_{C}	Large-signal collector current
i_{e}	Incremental emitter current
i_{f}	Incremental feedback current
i_{F}	Large-signal feedback current
i_{s}	Incremental source current
J_{l}	Illumination on a surface per unit wavelength
J_{r}	Irradiation on a surface per unit wavelength
j or i	$\sqrt{-1}$
K	Stability factor $dI_{\mathrm{C}}/dI_{\mathrm{CEO}}$
L	Inductance
L_{l}	Leakage inductance of a transformer
L_{m}	Magnetizing inductance of a transformer

mA	Milliamps
mW	Milliwatts

N	Number of turns
N_{P}	Number of turns on a transformer primary
N_{S}	Number of turns on a transformer secondary
NEP	Noise equivalent power (for a photocell)
n	Turns ratio of a transformer

O_{D}	Optical density
O_{T}	Optical transmission

P	Power
P_{diss}	Power dissipated within a transistor (or other device)
$P_{diss(FL)}$	Power dissipated within a transistor at full load
$P_{diss(Q)}$	Power dissipated within a transistor under quiescent conditions
P_{tot}	Maximum permissible power which may be dissipated within a transistor
P_{L}	Power supplied to a load
P_{S}	Power extracted from a power supply
PRF	Pulse repetition frequency
PSC	Position-sensitive cell
pF	Picofarad (10^{-12} farad)

Q	Charge	
Q	Selectivity	
Q_{B}	Base charge	Charge control parameters
Q_{BS}	Stored base charge	
Q_{ON}	Switch-ON charge	
Q_{V}	Base charge due to a change in V_{CB}	

R	Resistance
R_{B},	External resistances in the base circuit of a transistor
R_{BP}	R_{B} combined with R_{in}
R_{C}	External resistance in the collector circuit of a transistor
R_{CES}, R_{CS}	Internal collector-emitter resistance of a saturated transistor
R_{D}	External resistance in the drain circuit of a FET
R_{DS}	Internal drain-source resistance of a FET
R_{E}	External resistance in the emitter circuit of a transistor
R_{F}	External feedback resistance
R_{G}	External resistance in the gate circuit of a FET
R_{g}	Internal resistance of a source
R_{in}	Input resistance of an amplifier or other network
R_{L}	Load resistance
R_{S}	Load connected to the secondary of a transformer
R_{1}	Winding resistance of a transformer

R_m	Resistive component of the magnetizing impedance of a transformer	
R_{OFF}	OFF resistance of a semiconductor device	
R_{ON}	ON resistance of a semiconductor device	
R_{out}	Output resistance of an amplifier or other network	
R_S	Source resistance (usually includes R_g and other resistances)	
R_X	Common resistance in the emitter circuit of a difference amplifier	
R_Z	Chord or d.c. resistance of a Zener diode	
r_e, r_b, r_c, r_m	The T-parameters	
$r_{bb'}$	Base spreading resistance (from the hybrid-π equivalent)	
r_z	Incremental resistance of a Zener diode	
S	Stability factor, dI_C/dI_{CBO}	
SCR	Silicon controlled rectifier, or thyristor	
S_1	Specific responsivity (of a photocell)	
S_L	Load stability factor	for power supplies
S_T	Temperature stability factor	
S_V	Transfer stabilization factor	
T	Temperature	
T_{amb}, T_a	Ambient temperature	
T_c	Case temperature	
T_j	Collector junction temperature	
T_s	Temperature of heat sink	
t	Time	
t_d	Delay time	Switching parameters
t_f	Fall time	
t_r	Rise time	
t_s	Storage time	
t_{ON}	ON time	
t_{OFF}	OFF time	
V	Voltage, d.c. or r.m.s. a.c.	
V_B	Voltage at a base with reference to some datum (usually the common line)	
V_{BB}	Voltage across the 'bases' of a Unijunction transistor	
V_{BE}	Base-emitter voltage	
V_C	Voltage at a collector with reference to some datum (usually the common line)	
V_{CB}	Collector-base voltage	
V_{CBM}	Maximum allowed collector-base voltage for a transistor	
V_{CC}	Supply voltage	
V_{CE}	Collector-emitter voltage	
V_{CEM}	Maximum allowed collector-emitter voltage for a transistor	
$V_{CE(m)}$	Maximum value which V_{CE} may reach in a circuit	

V_{CES}	Value of V_{CE} at saturation
V_{D}	Forward voltage across a diode
V_{DS}	Drain-source voltage for a FET
V_{E}	Voltage at an emitter with reference to some datum (usually the common line)
V_{EB}	Emitter-base (reverse) voltage
V_{EBM}	Maximum allowed emitter-base (reverse) voltage
V_{EC}	Emitter-collector, or offset, voltage of a chopper transistor
V_{GD}	Gate-drain voltage for a FET
V_{GS}	Gate-source voltage for a FET
V_{in}	Voltage at the input point of an amplifier (or other network)
V_{O}	Cut-off voltage for a FET
V_{P}	Pinch-off voltage for a FET
V_{Q}	Quiescent or no-signal value of V_{CE}
V_{Z}	Zener diode voltage
v	Incremental or small signal voltage
v_{be}	Incremental or small signal base-emitter voltage
v_{BE}	Large signal base-emitter voltage
v_{ce}	Incremental or small signal collector-emitter voltage
v_{f}	Incremental or small signal feedback voltage
v_{in}	Incremental or small signal input voltage
v_{out}	Incremental or small signal output voltage
W_{g}	Width of energy gap
W_{f}	Work function
X	Reactance
$X_{C_{\mathrm{C}}}$	Reactance of coupling capactior
$X_{C_{\mathrm{E}}}$	Reactance of emitter capacitor
Y_{B}	Admittance in base circuit, $1/Z_{\mathrm{B}}$
Y_{L}	Load admittance, $1/Z_{\mathrm{L}}$
Y_{out}	Output admittance of an amplifier (or other network), $1/Z_{\mathrm{out}}$
Z	Impedance
Z_{B}	Impedance in base circuit
Z_{F}	Feedback impedance
Z_{in}	Input impedance of an amplifier (or other network)
Z_{out}	Output impedance of an amplifier (or other network)
Z_{L}	Load impedance
Z_{S}	Source impedance
$\bar{\alpha}, \bar{\alpha}', \bar{\alpha}''$	D.C. current gains for CB, CE and CC modes
$\alpha, \alpha', \alpha''$	Incremental or small signal current gains for CB, CE and CC modes

$\bar{\beta}$	Ratio of carriers reaching collector to those leaving emitter (Note: in many texts this symbol is used as follows: $\bar{\beta} = \bar{\alpha}'$ and $\beta = \alpha'$)	
$\bar{\gamma}$	Emitter efficiency	
η	Intrinsic stand-off ratio for a Unijunction transistor	
θ	Thermal resistance	
θ_{jc}	Thermal resistance, junction to case, for a semiconductor device	
θ_{cs}	Thermal resistance, case to sink, for a semiconductor device	
θ_{sa}	Thermal resistance, sink to ambient, for a heat sink, or cooler	
θ_{t}	Total thermal resistance	
θ_{Z}	Temperature coefficient of a Zener diode	
λ	Wavelength of electromagnetic radiation	$\lambda\nu$ = velocity of light, c
ν	Frequency of electromagnetic radiation	
Φ	Magnetix flux	
Φ_{sat}	Magnetic flux when core is saturated	
ϕ	Phase angle	
τ_{c}	Collector time factor	
τ_{co}	Collector time factor measured at $V_{\mathrm{CB}} = 0$	Charge control parameters
τ_{s}	Saturation time factor	

CONTENTS

Symbols and abbreviations ix
1 The scope of semiconductor devices 1
2 Physical principles and d.c. characteristics of diodes and transistors 8
3 Small signal parameters and equivalent circuits 24
4 The transistor as an amplifier 36
5 Small signal and feedback amplifiers 57
6 Special purpose amplifiers 92
7 The transistor as a switch 168
8 Power supplies 212
9 Semiconductor light transducers 240
10 Other semiconductor devices and applications 266
11 Transistor electronics for some electro-optical instruments 292

Appendix I: Classical circuit concepts 298
Appendix II: Four-pole parameters 311
Index 315

Chapter 1

The Scope of Semiconductor Devices

Diodes

Analogies between semiconductor devices and thermionic valves are often decried; they can lead to errors in design. But while valves remain common, the analogies will be drawn, and so their limitations must be recognized. The most elementary form taken by the valve is the diode, largely familiar as a small power rectifier used for converting a.c. to unidirectional current. The conventional symbol is given in Fig. 1.1(*a*) though occasionally, when a small thermionic diode is used as a signal rectifier, the symbol of Fig. 1.1(*c*) may be used. Usually, for small power rectification, a second anode is added to form a full-wave diode, and the symbol takes the form shown in Fig. 1.1(*b*).

The equivalent semiconductor diode is always represented by the symbol shown in Fig. 1.1(*c*), since it consists solely of a single crystal of a semiconductor material such as a silicon or germanium, the anode and cathode being differentiated only by the nature of certain added impurities. The semiconductor diode is very much smaller than a thermionic diode of similar performance, as the comparison given in Table 1.1 shows.

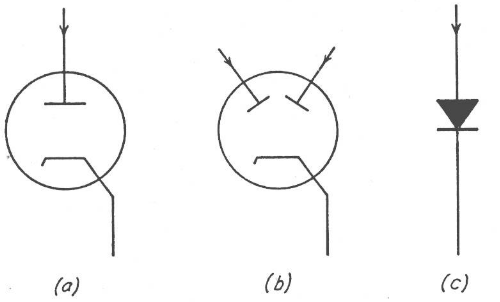

Fig. 1.1. Diode symbols for (*a*) half-wave valve rectifier, (*b*) full-wave valve rectifier and (*c*) semiconductor rectifier. (Small arrows indicate direction of conventional current flow.)

The efficiency of the semiconductor diode is much higher than that of the valve, mainly owing to the absence of a heater, and the voltage drop is much lower. On the other hand, like all semiconductor devices, it is extremely sensitive to temperature, and the maximum permissible current drops to 165 mA at 75°C for the example in Table 1.1.

The maximum voltage and current ratings for semiconductor devices are very rigid and must not be exceeded, even temporarily, otherwise permanent damage to the device will normally result. For example, at full load, the DD006 will dissipate

250 × 0·5 = 125 mW at 25°C, and if this is exceeded, the low thermal capacity of the device, engendered by its small size, will cause it to heat up and disrupt. In contrast, though the heat dissipated by a GZ30 is much higher (0·125 × 18 = 2·25 W + that due to the heater), a transient overload of reasonable magnitude will have little effect.

Table 1.1 Comparison of typical small-power rectifiers

	Full-wave thermionic diode (Mullard GZ30)	Silicon diode (Lucas DD006)
Maximum voltage	350 V each section	400 V
Maximum current	125 mA	250 mA (at 25°C)
Voltage drop at full load	18 V	0·5 V
Size	3·8 inches (length) × 1·2inches (diameter)	0·2 inch (length) × 0·2 inch (diameter)

The semiconductor diode will also fail if an over-voltage is applied, again even transiently, whereas the valve will not suffer.

However, it can be seen that the semiconductor diode, provided it is *always* operated within its ratings, has significant advantages.

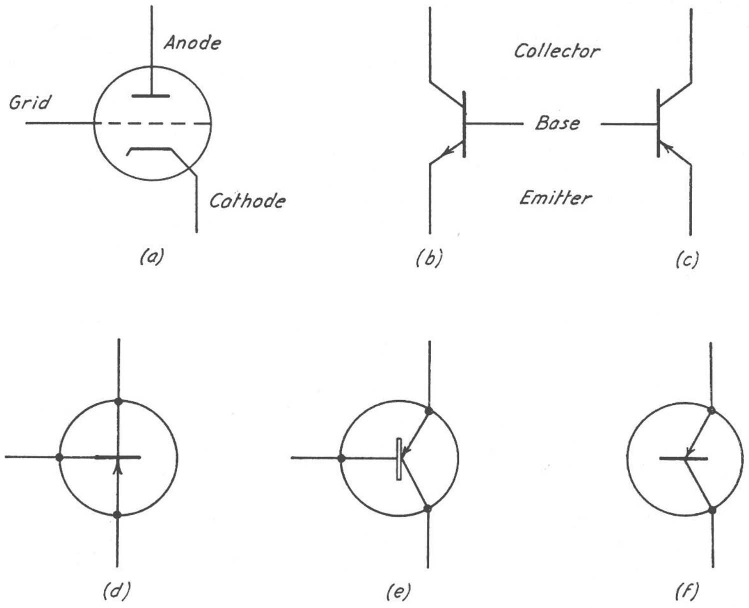

Fig. 1.2. Triode and transistor symbols. (*a*) Triode. (*b*) NPN transistor. (*c*) PNP transistor. (*d*), (*e*) and (*f*) Alternative transistor symbols.

Transistors

The above remarks apply also to the transistor, which is a three-electrode solid-state device in many ways analogous to the thermionic triode or pentode. Fig. 1.2 shows the symbol for a triode, and the most common symbols for transistors. The diagram is oriented so as to stress the analogy between the functions of the various electrodes. Thus, the cathode, the anode, and the grid of the valve correspond respectively to the emitter, the collector, and the base of the transistor. Figs. 1.3(*a*) and (*b*) indicate how the valve and the transistor may be connected to give a gain in voltage from input to output, and again stress the analogy between the two devices. However, like all analogies, it must not be taken too far, and Fig. 1.3(*b*) indicates that the base current of the transistor is *not zero* as is the grid current for a valve. In fact, the bias *voltage* on the grid of a valve is analogous to the bias *current* flowing in the base of a transistor. In Fig. 1.3(*b*), this current flows into the base of the transistor, and out of the emitter. Thus, the bias battery is connected in the opposite sense to that of the valve circuit. The correct sense is apparent in the symbol for the transistor, which has an arrow showing the direction of current in the emitter. Thus, the base and collector currents combine to form the emitter current.

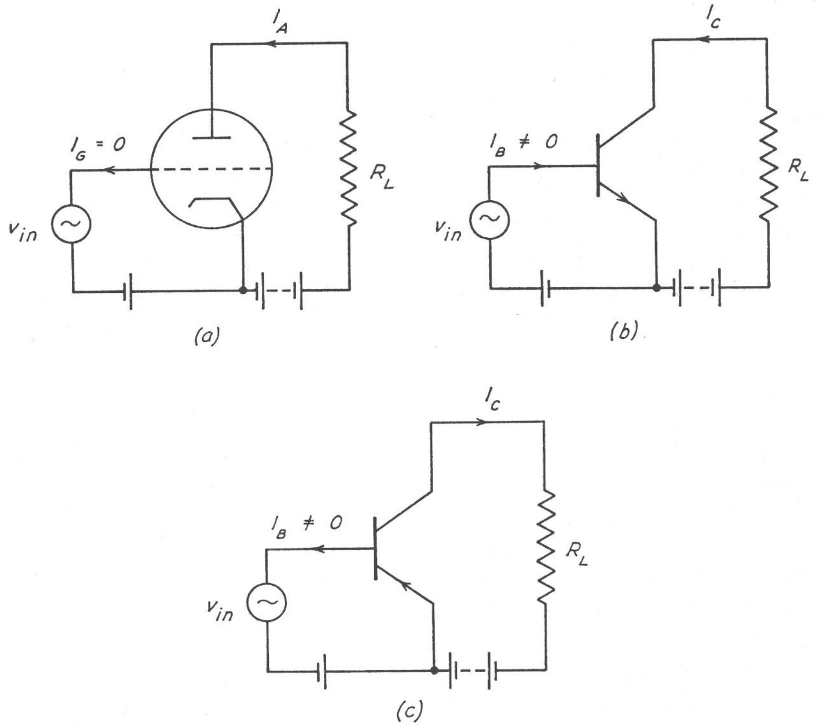

Fig. 1.3. Simple amplifier circuits for (*a*) triode amplifier, (*b*) NPN transistor amplifier (common-emitter mode) and (*c*) PNP transistor amplifier (common-emitter mode).

The NPN transistor depicted symbolically in Figs. 1.2(*b*) and 1.3(*b*) has a mirror-image dual—the PNP transistor. This can be treated in precisely the same way as the NPN device, except that all voltages and currents are reversed as shown in Fig. 1.3(*c*). There is no thermionic device in which this situation could occur, for this would presuppose an anti-matter universe where the charge carriers were positrons. This illustrates the great versatility of semiconductor elements; for it is apparent that either positive or negative supplies can be used, and that the polarity of the output signal is open to choice.

The major differences in the operation of valves and transistors are summarized in Table 1.2.

Table 1.2 Comparison of valve and transistor

	Valve	Transistor
H.T. supply	High (typically 300 V)	Low (typically 12 V)
Input impedance	Very high (many MΩ)	Low (typically 500 Ω)
Currents	Low (*Ia* typically 1–50 mA)	High (*Ic* typically 1 mA–6 A)
Load impedance	High (typically 100 kΩ)	Low (typically 5 kΩ)
Heat dissipation	High	Low

This comparison is, of course, not by any means inviolate, but depends on the device and the circuit configuration involved. For example, field-effect transistors (see Chapter 10) have input impedances of several hundreds of megohms, and circuits can be designed, using normal transistors, to give input impedances of tens or even hundreds of megohms. Similarly, valve amplifiers can be designed to have input impedances of a fraction of an ohm. The table nevertheless gives an indication of the quantities to be expected in the simpler configurations.

The low voltages and high currents involved in transistor circuitry have led to the development of high-capacity, low-voltage electrolytic capacitors. Values of tens, hundreds, or thousands of microfarads at working voltages of six or twelve are now commonplace, and remarkable reductions in size and cost have kept pace with the new requirements.

Voltage References

Much electronic equipment necessitates power supplies giving direct voltages which do not change with fluctuations in the mains input voltage, or with the current drawn by the load. Such stabilized power packs rely for their stability on some voltage reference; in valve supplies, this is usually a gas-filled voltage reference tube. Where a lower degree of stabilization is required, a voltage regulator tube may be employed; this acts essentially as a variable load which governs the voltage produced by controlling the drop in a series resistor.

The semiconductor equivalents of such devices are the Zener and avalanche diodes. These are semiconductor diodes constructed in such a manner that when the reverse voltage applied is high enough to break down the diode, no permanent damage results, providing, of course, that the power dissipated is kept within the recommended limit. This breakdown, or *turnover* voltage, is remarkably constant, irrespective of current, and it is this characteristic that makes the device useful as a voltage regulator. Fig. 1.4 gives the most usual symbols for the gas tube and the Zener diode. It will be seen that the Zener symbol is a modification of that for the normal diode. Note that the arrow showing the direction of current flow is in opposition to the normal direction of current flow in a diode, which indicates that the diode has broken down and that a reverse current is flowing.