HANDBOOK OF NUCLEAR MEDICAL INSTRUMENTS

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Handbook of

NUCLEAR MEDICAL INSTRUMENTS

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PREFACE

The book is a compilation of the edited text of the lectures delivered by the experts during the 'IAEA RCA Workshop on Nuclear Medical Instrument Maintenance' held at BARC during Jan. 15 – Feb. 2, 1990. Considering the importance of the subject, additional relevant information has been provided to make it a versatile reference manual. Effort has been made to keep the matter simple and self explanatory to the extent possible with the help of diagrams. The theory of operation of instruments and practical maintenance hints have been highlighted to increase availability of instruments.

The present volume is a revised and expanded version of the earlier edition published in 1991. The professionals have presented in a lucid manner, their years of experience with nuclear medical instruments. The text has been restructured based on the feedback received from eminent specialists, to provide better understanding and appreciation of the subject. The book can serve as a ready reference for the technologists and medical physicists in nuclear medicine centres. It can also be used as a text book in the college curriculum.

The Chapters 1 to 3 deal with the basic principles of nuclear electronics, counting systems and general test equipment. Radiation detectors used in nuclear medicine are explained in Chapter 4. After giving an introduction to the principles of in vivo techniques in Chapter 5, the regular treatment of nuclear medical diagnostic instruments is given in Chapter 6 to 10. The discussion covers the equipment in the increasing order of sophistication. These include the simple isotope calibrator unit, uptake monitoring instrument, rectilinear scanner, gamma scintillation camera and also the state of art advanced single photon emission computed tomography system. Next, the principles of in vitro techniques are outlined in Chapter 11. Thereafter the illustrations of radioimmunoassay and liquid scintillation counting systems are given in Chapters 12 and 13.

The description of Radiopharmaceuticals for diagnostic applications is given in Chapter 14. This is followed by the explanation of the use of computers in nuclear medicine given in Chapter 15. Quality Assurance procedures are briefly covered in Chapter 16. The less emphasized, yet an important aspect of radiation protection in nuclear medicine is presented in Chapter 17. Methods of providing conducive environment for the proper operation of nuclear medical equipments are given in Chapters 18 to 20. These comprise a.c. power line conditioning, environmental conditioning and preventive maintenance planning techniques. In Chapters 21 and 22, principles of electronic fault diagnosis and computer aids available for the equipment maintenance scheduling are outlined. Experiments listed in Chapters 23 and 24 are intended to provide hands on experience with the operation and performance evaluation of basic nuclear electronic measuring instruments and gamma ray spectrometer.

We are grateful to Dr.(Mrs.) A.M. Samuel, Head of Radiation Medicine Centre for her valuable suggestions and guidance. Our sincere thanks are due to Mr. Y. Xie of the Division of Life Sciences, IAEA, Vienna for his continued support and editorial help. We also record our appreciation to Dr. O.P.D. Noronha for contributing the chapter on radiopharmaceuticals which has added to the utility of the book. We thank the Department of Atomic Energy and International Atomic Energy Agency for providing funds, facilities and encouragement. We offer our sincere appreciation to Mr. C.M. Menezes and others who have offered technical help in bringing out this publication.

BARC, Bombay.

B.R. Bairi

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Chapter 1

PRINCIPLES OF NUCLEAR ELECTRONICS

1.1 ANALOG CIRCUITS

All electronic circuits make use of some basic electronic components like resistors(R), capacitors(C), inductors(L), diodes(D), transistors(T), integrated circuits(IC), etc. Any combination of resistors, inductors and capacitors can be represented by an equivalent impedance Z as shown in *fig. 1.1*. Whenever a voltage V is applied across the impedance Z, the current I flows through it. This current is equal to V divided by Z.

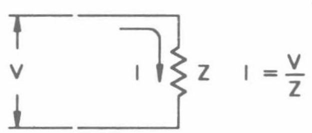

Fig. 1.1 Equivalent impedance representation

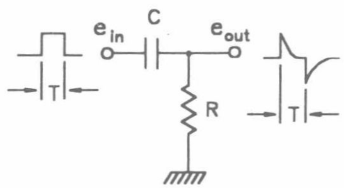

Fig. 1.2 R-C differentiator

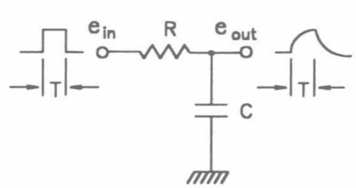

Fig. 1.3 R-C integrator

Most commonly used passive circuits are the R-C differentiator and R-C integrator as shown in *fig. 1.2 and 1.3* respectively. These circuits are often used for shaping the electronic pulses from nuclear radiation detectors. The circuit shown in *fig. 1.2* works as a differentiator for the input pulse having a maximum frequency component of ω, where $\omega << 1/RC$.

$$e_{out} = RC \frac{d(e_{in})}{dt}$$

Similarly the circuit shown in *fig. 1.3* works as an integrator for the input pulse having the minimum frequency component ω, where $\omega >> 1 / RC$.

$$e_{out} = \frac{1}{RC} \int_0^t i \, dt$$

To overcome the limitations of frequency, active differentiators and integrators are used, which are described in a section on operational amplifier. The circuit shown in *fig. 1.2* is also used as a simple high pass filter and the one shown in *fig. 1.3* is used as a simple low pass filter.

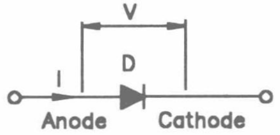

Fig. 1.4 Diode

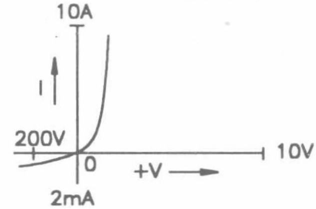

Fig. 1.5 Diode characteristic

Other commonly used devices are diodes and transistors. A diode is shown in *fig. 1.4*. A diode conducts only in one direction i.e., it allows the flow of current through it only if its anode is more positive with respect to the cathode. If the cathode is made positive with respect to the anode, the flow of current through the diode is inhibited. Thus a diode exhibits the characteristic shown in *fig. 1.5*. Because of this property, the diode is used as a rectifier.

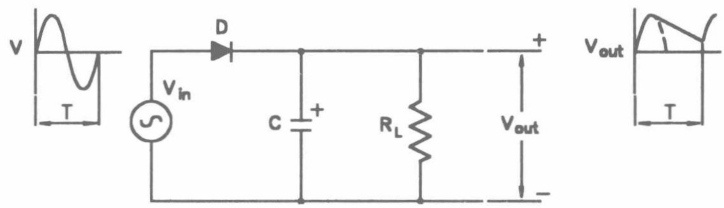

Fig. 1.6 Halfwave rectifier

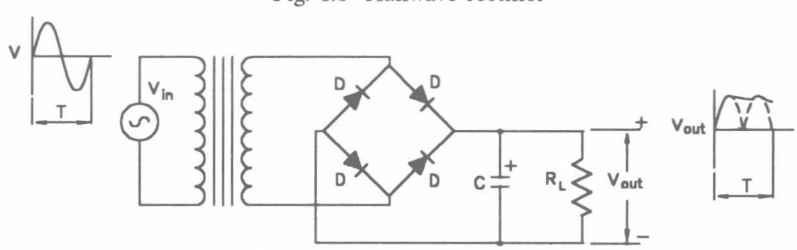

Fig. 1.7 Fullwave bridge rectifier

A typical half wave rectifier circuit and a full wave bridge rectifier circuit are shown in *fig. 1.6* and *fig. 1.7* respectively. The rectified output is smoothened using a capacitance filter to reduce the ripple.

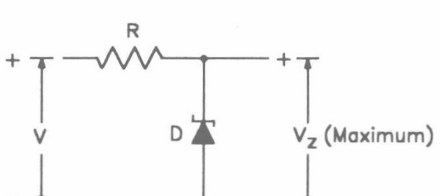

Fig. 1.8 Zener diode

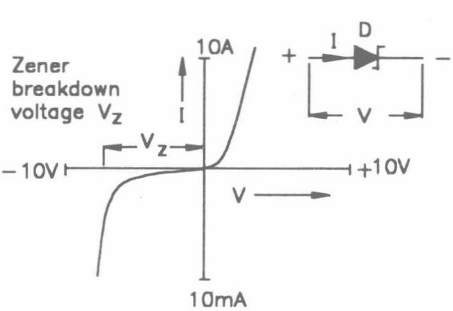

Fig. 1.9 Zener characteristic

A zener diode D with a biasing resistance R is shown in *fig. 1.8*. The zener diode exhibits a different characteristic when reverse biased. This is shown in *fig. 1.9*. This property of the zener diode is utilized for voltage regulation. Thus, if an unregulated voltage V_{in} is applied to the input of a circuit shown in *fig. 1.10*, the output voltage will always be equal to V_z, provided V_{in} is greater than V_z.

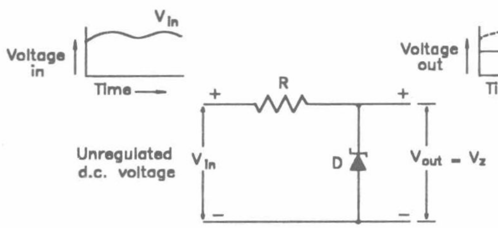

Fig. 1.10 Zener voltage regulator

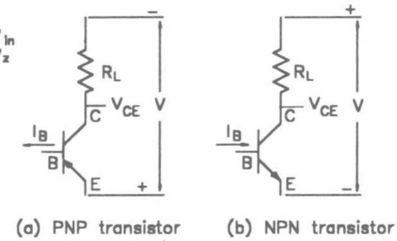

Fig. 1.11 Bipolar transistor

Bipolar transistors are classified as PNP andNPN types as shown in *figs. 1.11a and b* respectively.

Typical transistor characteristics are shown in *fig. 1.12*. Transistors are used in electronic circuits for many applications. Basically a transistor circuit configuration can be classified as the (i) common base, (ii) common emitter or (iii) common collector, as shown in *fig.1.13a, b and c* respectively. In the common base configuration, the transistor is used as a voltage amplifier. In the common emitter configuration, the transistor can be used for both voltage and current amplification. In the common collector mode, it is used as a current amplifier.

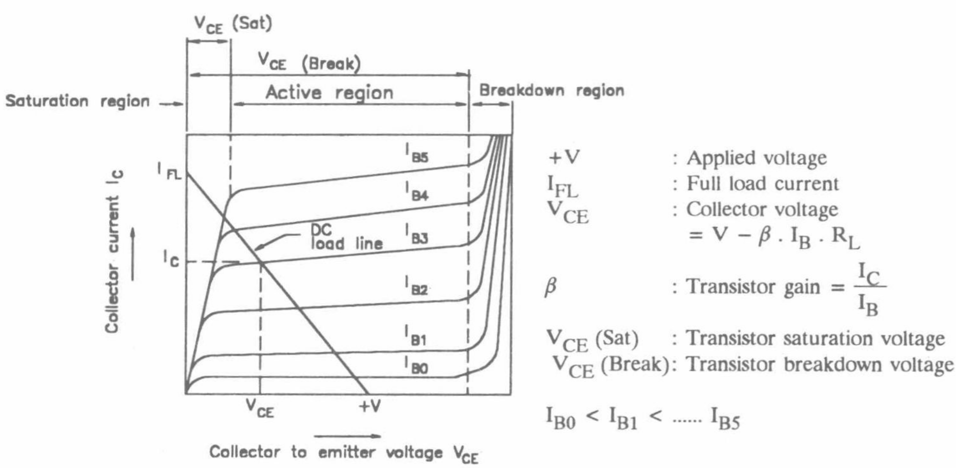

Fig. 1.12 Characteristics of a typical bipolar transistor

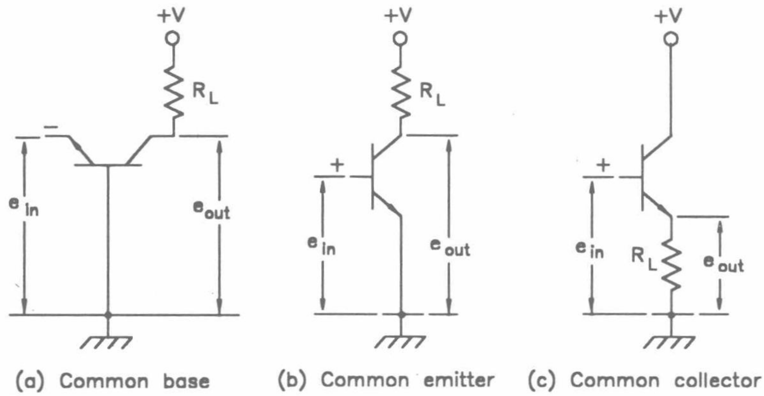

Fig. 1.13 Bipolar transistor amplifier configurations

A bipolar transistor is also used as an ON/OFF switch. When both the base-emitter and base-collector junctions of a transistor are reverse biased, the impedance experienced between the emitter and collector is very large and the transistor behaves as a switch in an OFF condition. Similarly, when both base-emitter and base-collector junctions of a transistor are forward biased, very low impedance is experienced between the collector and emitter and the transistor behaves like a switch in the ON condition. This is illustrated in *fig. 1.14*.

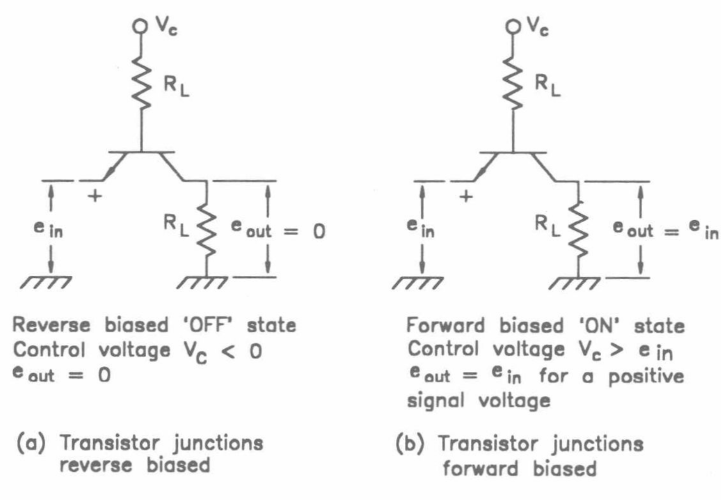

Fig. 1.14 Bipolar transistor used as an ON and OFF switch

A junction field effect transistor (JFET) is also a three terminal device having a source, a gate and a drain as shown in fig. 1.15a. The output characteristics of an n-channel JFET are shown in fig. 1.15b.

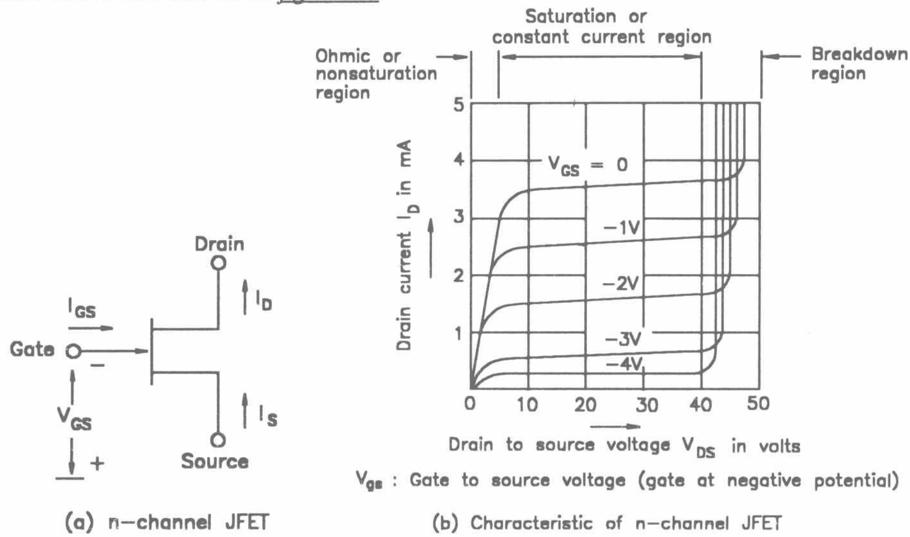

Fig. 1.15 Junction field effect transistor

The metal oxide semiconductor type FET is shown in fig. 1.16a. The output characteristics of the NMOS FET are shown in fig. 1.16b. The main advantage of an FET over the bipolar transistor is that FET provides a very high impedance at the input gate. It has no offset voltage and can switch the current in either direction.

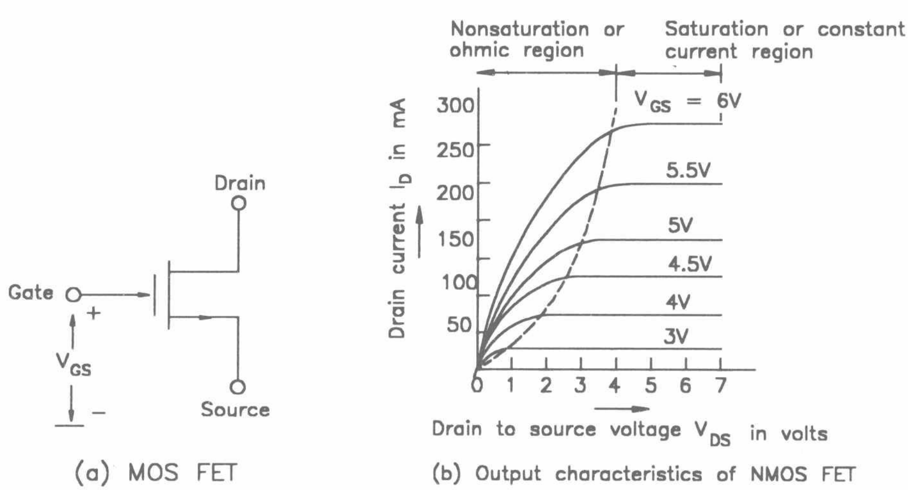

Fig. 1.16 MOS field effect transistor

Bipolar transistors are widely used in analog circuits in nuclear electronics as in preamplifiers, fast amplifiers, spectroscopy amplifiers, etc. Field effect transistors are mostly used in low-noise preamplifiers, as well as in pulse stretchers because of their low leakage current characteristics. MOS FETs are useful for very low bias current applications like in electrometer amplifiers and low current measurements.

1.1.1 Regulated Voltage Supply

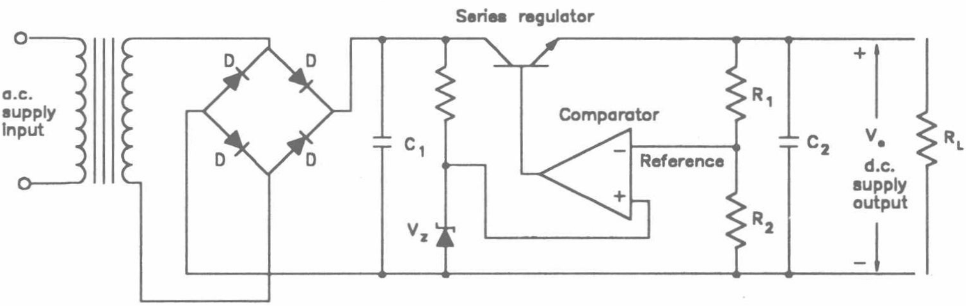

Fig. 1.17 Regulated power supply

Fig. 1.17 shows a typical d.c. regulated voltage supply, which uses a fullwave bridge rectifier. The zener diode provides a stable reference voltage V_z. For achieving output voltage regulation, a fraction of the output voltage is compared with V_z using an operational amplifier comparator. The output of an operational amplifier is fed to the base of a transistor regulator which is connected in series with the load. Thus, the voltage between emitter and collector of this transistor is controlled, keeping the output voltage constant.

In nuclear electronics, the regulated low voltage power supplies of ±5V, ±6V, ±12V and ±24V are used to supply current for various analog and digital circuits. The regulated high voltage power supplies, ranging from 500V to 2500V, are used for biasing nuclear detectors and photomultiplier tubes.

1.1.2 Operational Amplifiers

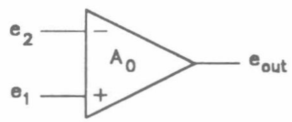

Fig. 1.18 Operational amplifier

Operational amplifiers are available in the IC (Integrated circuit) form and are used as basic building blocks in many electronic circuits like amplifiers, single channel analyzers, peak stretchers, etc. An operational amplifier (OP) is basically a differential amplifier having two inputs and a single output as shown in *fig. 1.18*.

The output of an operational amplifier is $A_o(e_1 - e_2)$, where A_o is the open loop gain of the amplifier and e_1 and e_2 are the voltages at the non-inverting (+ve) and inverting (−ve) terminals of the OP respectively.

The characteristics of an ideal operational amplifier are

(i) Open loop gain is infinity.
(ii) Input impedance is infinity.
(iii) Bandwidth is infinity.
(iv) Output impedance is zero.
(v) Bias current (drive current required at input terminals of an OP) is zero.

The most common circuits making use of operational amplifiers are described below

(a) Inverting amplifier (*fig. 1.19*)

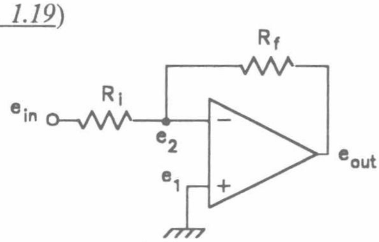

Fig. 1.19 Inverting amplifier

$$e_{out} = - (e_2 - e_1) \times A_0$$

hence $$e_2 - e_1 = -\frac{e_{out}}{A_o}$$

e_{out} is finite and A_o is infinite for an ideal operational amplifier

thus $$e_2 = e_1 = 0.$$

Hence, the current flowing through R_i is given by i,

where $$i = \frac{(e_{in} - e_2)}{R_i} = \frac{e_{in}}{R_i}$$

Same current i, flows through R_f (since the bias current of an OP is zero).

hence, $$e_{out} = e_2 - R_f\, i\,,$$

which gives $$e_{out} = -\frac{R_f}{R_i}\, e_{in}$$

where e_{in} and e_{out} are the input and output voltages respectively.

Similarly, for other configurations of an operational amplifier, the following relationships can be proved.

(b) Non inverting amplifier (*fig. 1.20*)

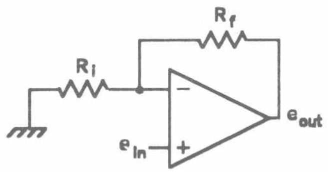

Fig. 1.20 Non-inverting amplifier

$$e_{out} = e_{in}\frac{R_f + R_i}{R_i}$$

(c) Difference amplifier (*fig. 1.21*)

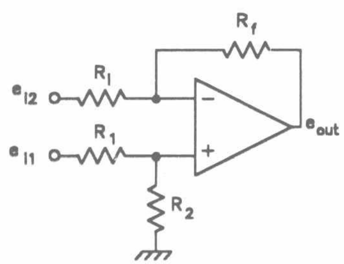

Fig. 1.21 Difference amplifier

$$e_{out} = (e_{i1} - e_{i2})\frac{R_f}{R_i}$$

provided $\frac{R_f}{R_i} = \frac{R_2}{R_1}$

where e_{i1} and e_{i2} are the input voltages and e_{out} is the output voltage.

(d) Summing amplifier (*fig. 1.22*)

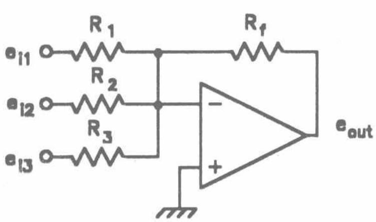

Fig. 1.22 Summing amplifier

$$e_{out} = -e_{i1}\frac{R_f}{R_1} - e_{i2}\frac{R_f}{R_2} - e_{i3}\frac{R_f}{R_3}$$

when $R_1 = R_2 = R_3$,

then $e_{out} = -(e_{i1} + e_{i2} + e_{i3})\frac{R_f}{R_1}$

thus the output voltage is proportional to the sum of input voltages.

(e) Differentiator (*fig. 1.23*)

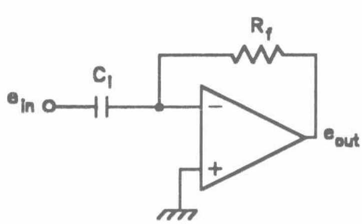

Fig. 1.23 Differentiator

$$e_{out} = -R_f C_i \frac{d(e_{in})}{dt}$$

The circuit is also used as a high pass filter since the gain increases with the frequency.

(f) Integrator (*fig. 1.24*)

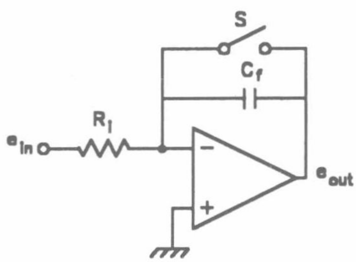

Fig. 1.24 Integrator

$$e_{out} = -\frac{1}{R_i C_f} \int_0^t e_{in}\, dt$$

The circuit is also used as a low pass filter, since the gain decreases with the frequency. The switch S is used to discharge the capacitor to the initial state after integration.

(g) Millivolt precision rectifier

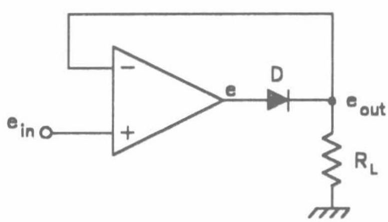

Fig. 1.25 Millivolt precision rectifier

In the circuit shown in *fig. 1.25*, when the input voltage e_{in} is positive, the diode D gets forward biased and it conducts. The feedback loop gets closed, and the circuit works like a unity gain non-inverting amplifier(buffer). Hence $e_{out} = e_{in}$. However, when e_{in} is negative, the output e of the operational amplifier becomes negative and reverse biases the diode D. The feedback loop is thus opened and $e_{out} = 0$.

(h) Peak detector

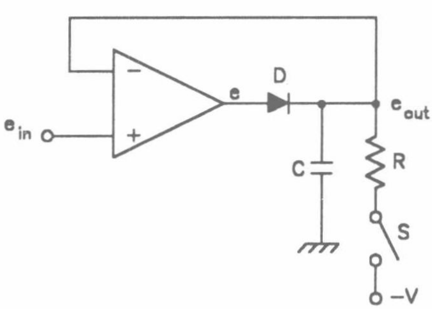

Fig. 1.26 Peak detector

The circuit in *fig. 1.26* is utilized to detect the peak height of input pulse of positive polarity. The switch S is normally closed, so that the current flows through R due to the application of voltage $-V$. Because of this, the diode conducts and $e_{out} = e_{in}$ provided the voltage e_{in} is positive with respect to $-V$. As soon as the input pulse arrives, its presence is detected by a separate comparator, and switch S is opened. Voltage e_{out} still tracks e_{in} and the capacitor C gets charged to the same voltage, till the peak of the pulse occurs. After reaching the peak value, the input pulse height starts decreasing. The output voltage, however, is not able to decrease because the voltage e becomes less than e_{out} and the diode gets reverse biased. Thus the output voltage of the operational amplifier is held at the peak value of e_{in}, till the switch S is closed again for detecting the peak height of the next input pulse.