THE ART [illegible]

[illegible]

Paul Horowitz HARVARD UNIVERSITY

Winfield Hill ROWLAND INSTITUTE FOR SCIENCE, CAMBRIDGE, MASSACHUSETTS

CAMBRIDGE UNIVERSITY PRESS

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, Victoria 3166, Australia

First published 1980
Second edition 1989
Reprinted 1990 (twice), 1991, 1993

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data

Horowitz, Paul, 1942–
The art of electronics / Paul Horowitz, Winfield Hill. – 2nd ed.
p. cm.
Bibliography: p.
Includes index.
ISBN 0-521-37095-7
1. Electronics. 2. Electronic circuit design. I. Hill, Winfield. II. Title.
TK78155.H67 1989
621.381 – dc19 89-468
CIP

British Library Cataloguing in Publication Data

Horowitz, Paul, 1942–
The art of electronics. – 2nd ed.
1. Electronic equipment
I. Title. II. Hill, Winfield
621.381

ISBN 0-521-37095-7 hardback

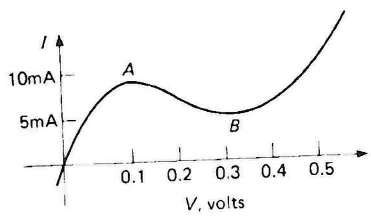

Figure 1.15

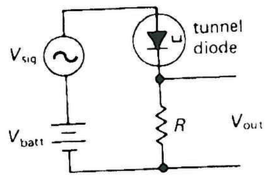

Figure 1.16

a tunnel diode can actually be an *amplifier* (Fig. 1.16). For a wiggly voltage v_{sig}, the voltage divider equation gives us

$$v_{\text{out}} = \frac{R}{R + r_t} v_{\text{sig}}$$

where r_t is the incremental resistance of the tunnel diode at the operating current, and the lower-case symbol v_{sig} stands for a small-signal variation, which we have been calling ΔV_{sig} up to now (we will adopt this widely used convention from now on). The tunnel diode has $r_{t(\text{incr})} < 0$. That is,

$$\Delta V / \Delta I \quad (\text{or } v/i) \quad < \quad 0$$

from A to B on the characteristic curve. If $r_{t(\text{incr})} \approx R$, the denominator is nearly zero, and the circuit amplifies. V_{batt} provides the steady current, or *bias*, to bring the operating point into the region of negative resistance. (Of course, it is always necessary to have a source of power in any device that amplifies.)

A postmortem on these fascinating devices: When tunnel diodes first appeared, late in the 1950s, they were hailed as the solution to a great variety of circuit problems. Because they were fast, they were supposed to revolutionize computers, for instance. Unfortunately, they are difficult devices to use; this fact, combined with stunning improvements in transistors, has made tunnel diodes almost obsolete.

The subject of negative resistance will come up again later, in connection with active filters. There you will see a circuit called a negative-impedance converter that can produce (among other things) a pure negative resistance (not just incremental). It is made with an operational amplifier and has very useful properties.

SIGNALS

A later section in this chapter will deal with capacitors, devices whose properties depend on the way the voltages and currents in a circuit are *changing*. Our analysis of dc circuits so far (Ohm's law, Thévenin equivalent circuits, etc.) still holds, even if the voltages and currents are changing in time. But for a proper understanding of alternating-current (ac) circuits, it is useful to have in mind certain common types of *signals*, voltages that change in time in a particular way.

1.07 Sinusoidal signals

Sinusoidal signals are the most popular signals around; they're what you get out of the wall plug. If someone says something like "take a 10 microvolt signal at 1 megahertz," he means a sine wave. Mathematically, what you have is a voltage described by

$$V = A \sin 2\pi f t$$

where A is called the amplitude, and f is the frequency in cycles per second, or hertz. A sine wave looks like the wave shown in Figure 1.17. Sometimes it is important to know the value of the signal at some arbitrary time $t = 0$, in which case you may see a *phase* ϕ in the expression:

$$V = A \sin(2\pi f t + \phi)$$

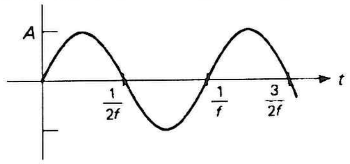

Figure 1.17. Sine wave of amplitude A and frequency f.

The other variation on this simple theme is the use of *angular frequency*, which looks like this:

$$V = A \sin \omega t$$

Here, ω is the angular frequency in radians per second. Just remember the important relation $\omega = 2\pi f$ and you won't go wrong.

The great merit of sine waves (and the cause of their perennial popularity) is the fact that they are the solutions to certain linear differential equations that happen to describe many phenomena in nature as well as the properties of linear circuits. A linear circuit has the property that its output, when driven by the sum of two input signals, equals the sum of its individual outputs when driven by each input signal in turn; i.e., if $O(A)$ represents the output when driven by signal A, then a circuit is linear if $O(A + B) = O(A) + O(B)$. A linear circuit driven by a sine wave always responds with a sine wave, although in general the phase and amplitude are changed. No other signal can make this statement. It is standard practice, in fact, to describe the behavior of a circuit by its *frequency response*, the way it alters the amplitude of an applied sine wave as a function of frequency. A high-fidelity amplifier, for instance, should be characterized by a "flat" frequency response over the range 20Hz to 20kHz, at least.

The sine-wave frequencies you will usually deal with range from a few hertz to a few megahertz. Lower frequencies, down to 0.0001Hz or lower, can be generated with carefully built circuits, if needed. Higher frequencies, e.g., up to 2000MHz, can be generated, but they require special transmission-line techniques. Above that, you're dealing with microwaves, where conventional wired circuits with lumped circuit elements become impractical, and exotic waveguides or "striplines" are used instead.

1.08 Signal amplitudes and decibels

In addition to its amplitude, there are several other ways to characterize the magnitude of a sine wave or any other signal. You sometimes see it specified by *peak-to-peak amplitude* (pp amplitude), which is just what you would guess, namely, twice the amplitude. The other method is to give the *root-mean-square amplitude* (rms amplitude), which is $V_{rms} = (1/\sqrt{2})A = 0.707A$ (this is for sine waves only; the ratio of pp to rms will be different for other waveforms). Odd as it may seem, this is the usual method, because rms voltage is what's used to compute power. The voltage across the terminals of a wall socket (in the United States) is 117 volts rms, 60Hz. The *amplitude* is 165 volts (330 volts pp).

Decibels

How do you compare the relative amplitudes of two signals? You could say, for instance, that signal X is twice as large as signal Y. That's fine, and useful for many purposes. But because we often deal with ratios as large as a million, it is easier to use a logarithmic measure, and for this we present the decibel (it's one-tenth as large as something called a bel, which no one ever uses). By definition, the ratio of two signals, in decibels, is

$$\text{dB} = 20 \log_{10} \frac{A_2}{A_1}$$

where A_1 and A_2 are the two signal amplitudes. So, for instance, one signal of twice the amplitude of another is +6dB relative

MATH REVIEW
APPENDIX B

Some knowledge of algebra and trigonometry is essential to understand this book. In addition, a limited ability to deal with complex numbers and derivatives (a part of calculus) is helpful, although not entirely essential. This appendix is meant as the briefest of summaries of complex numbers and differentiation. It is not meant as a textbook substitute. For a highly readable self-help book on calculus, we recommend *Quick Calculus*, by D. Kleppner and N. Ramsey (John Wiley & Sons, 1972).

COMPLEX NUMBERS

A complex number is an object of the form

$$\mathbf{N} = a + bi$$

where a and b are real numbers and i (called j in the rest of the book, to avoid confusion with small-signal currents) is the square root of -1; a is called the real part, and b is called the imaginary part. Boldface letters or squiggly underlines are sometimes used to denote complex numbers. At other times you're just supposed to *know*!

Complex numbers can be added, subtracted, multiplied, etc., just as real numbers:

$$(a+bi)+(c+di) = (a+c)+(b+d)i$$

$$(a+bi)-(c+di) = (a-c)+(b-d)i$$

$$(a+bi)(c+di) = (ac-bd)+(bc+ad)i$$

$$\frac{a+bi}{c+di} = \frac{(a+bi)(c-di)}{(c+di)(c-di)} = \frac{ac+bd}{c^2+d^2} + \frac{bc-ad}{c^2+d^2}i$$

All these operations are natural, in the sense that you just treat i as something that multiplies the imaginary part, and go ahead with ordinary arithmetic. Note that $i^2 = -1$ (used in the multiplication example) and that division is simplified by multiplying top and bottom by the *complex conjugate*, the number you get by changing the sign of the imaginary part. The complex conjugate is sometimes indicated with an asterisk. If

$$\mathbf{N} = a + bi$$

then

$$\mathbf{N}^* = a - bi$$

The magnitude (or *modulus*) of a complex number is

$$|\mathbf{N}| = |a+bi| = [(a+bi)(a-bi)]^{\frac{1}{2}} = (a^2+b^2)^{\frac{1}{2}}$$

i.e.,

$$|\mathbf{N}| = (\mathbf{N}\mathbf{N}^*)^{\frac{1}{2}}$$

simply obtained by multiplying by the complex conjugate and taking the square root. The magnitude of the product (or quotient) of two complex numbers is simply the product (or quotient) of their magnitudes.

The real (or imaginary) part of a complex number is sometimes written

real part of $\mathbf{N} = \mathcal{R}e(\mathbf{N})$
imaginary part of $\mathbf{N} = \mathcal{I}m(\mathbf{N})$

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase®
Smarter legal research.