of Table I and assuming that (1) $E_p \simeq 25$ eV,[11] and (2) F' centers have an activation energy of motion[12] of 0.6 eV, one obtains values of 4 sec eV^{-1} and 1.5×10^{19} cm^{-3} for the slope and intercept, respectively. Considering the order-of-magnitude nature of this calculation, the agreement of these values with experiment is considered quite good. Therefore, it is concluded that this mechanism is a reasonable one, as long as N_F and I are not too large.

From Eq. (6) it is evident that the temperature dependence of the intercept enters through $k_F'/D_{F'} \propto \exp[(E_M - E_{F'})/kT]$, and that of the slope through $1/D_{F'} \propto \exp(E_M/kT)$. A check of this model could be based upon this temperature dependence,[13] since the thermal ionization energy of F' centers is known[14] to be ~0.5 eV. Also, since Eq. (7) predicts a slope proportional to W_n/W_p^2, selective doping with an impurity that is dominantly an electron- or hole-capture center might afford another check on the model. Indeed, the value of N_F^2/N_M is markedly enhanced in Ca^{++}-doped specimens[4]; this is in the expected direction since an isolated Ca^{++} ion would have a large electron-capture probability for electrons and a negligible one for holes.

A previously suggested mechanism[9,15] based upon the anion vacancy (α center) as the moving entity interacting with F' centers was also examined. Although the steady-state solution has the proper form, the predicted value of N_F^2/N_M is too large by at least 10^7 because of the much larger energy of motion[16] of the α center. A detailed treatment of both mechanisms in which the assumptions and magnitudes are discussed is being prepared for publication.

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*Oak Ridge National Laboratory is operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

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ELECTRON BEAM EXCITATION OF GAS LASER TRANSITIONS AND MEASUREMENTS OF CROSS SECTIONS OF EXCITATION

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In this Letter we report on excitation of laser oscillations by a nearly monoenergetic electron beam emitted from a hot oxide cathode. We have observed laser oscillations at the 1.1526-μ line ($2s_2 - 2p_4$) in a helium and neon mixture and also of the 2.0261-μ line ($3d_2 - 2p_7$) in pure xenon. Such oscillations have been obtained previously only in glow discharges,[1,2] and there electrons have a wide spread of velocities. We have also measured single-path gains of the 1.1526-μ line in pure neon, and from the measurements we may calculate cross sections of excitation by direct electron impact at different electronic energies.

The energy of the electrons is controlled by a fine mesh grid which is parallel to the cathode and is spaced about $\frac{1}{2}$ mm from it. Also parallel to the cathode and located 4 mm above the grid is an anode [Fig. 1(a)] which, for reasons described later, is biased at a potential negative

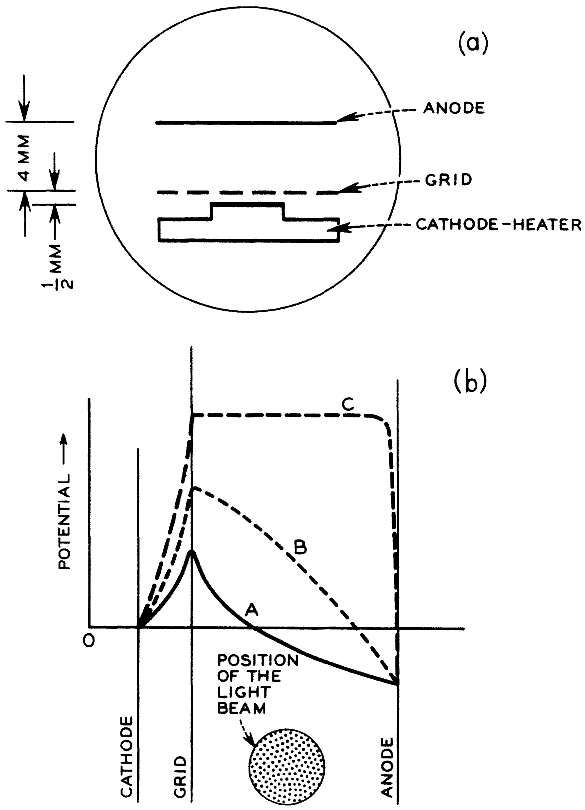

FIG. 1. (a) A cross-section view of the electrodes. (b) The potential distribution in the electron tube. Curve *A* shows the distribution in vacuum. Curve *B* indicates that the potential is raised when the gas begins to ionize. Curve *C* is the final potential distribution desired for laser excitation.

with respect to the cathode in all our experiments. The anode current thus measures the ion current. These electrodes are enclosed in a glass envelope having Brewster angle windows similar to those used in the usual gas laser of exterior mirrors.[3] The laser beam observed is parallel lengthwise to the electrodes and has a cross section about 1 mm in diameter. The cathode has a surface 4 mm wide and 18.75 cm long and is capable of delivering a current of 0.6 A at a grid potential of 30 V.

The potential distribution in the electron tube may be understood from Fig. 1(b). Consider the case when the tube is filled with neon. As we raise the grid potential above zero but below the ionization potential of neon, the current emitted from the cathode invades the grid-anode space and depresses the potential there according to the well-known space-charge law. The potential distribution is schematically shown by curve *A*. Also shown in Fig. 1 is the position of the light beam. We see that with such a potential distribution, the voltage drop across the light beam is at least 5 V, which is far too large for our purpose.

When we raise the grid potential further and finally above the ionization potential, the gas begins to ionize and produces electron-ion pairs. Because of high mobility, the electrons from ionization are swept out of the grid-anode space quickly and leave a positive ion cloud which raises the potential distribution in the space as shown by curve *B*. For convenience, electrons emitted from the cathode are denoted as "primary electrons" in order to distinguish them from those produced by ionization (secondary electrons). The primary electrons thus penetrate deeper into the grid-anode space, then ionize more gas atoms, and consequently raise the potential further. We thus observe a sudden current jump at the grid. The potential distribution finally reaches the form shown by curve *C*. A uniform potential distribution exists in the whole grid-anode space with the exception of thin sheath below the anode. The potential in the space is not raised further because, otherwise, it would trap electrons instead of ions. In the experiments, we observe a uniform glow between the grid and the anode except for a thin dark line immediately below the anode.

As shown by curve *C*, the primary electrons travel in a field-free grid-anode space, and their energy is accurately controlled by the grid potential.[4] The secondary electrons have relatively small energies and are not able to excite the laser states directly. In the later calculation, we first determine the density of the primary electrons from the measured grid and ion currents, and then calculate the cross section of excitation by ignoring all the second-order effects.[5] To measure cross sections of excitation below the ionization potential of neon, we mix with the neon a trace of argon or xenon which have ionization potentials of 15.76 V and 11.6 V, respectively, as compared with 21.56 V for neon. Ionization of the argon or xenon then provides the necessary ions to maintain constant potential near the light beam.

Figures 2(a), (b), and (c) show, respectively, the light output, the anode current, and the grid current observed in the laser oscillation of 2.0261-μ line of zenon. The pressure of xenon is 0.037 Torr. All the curves are the traces directly observed in a *X-Y* oscilloscope and are

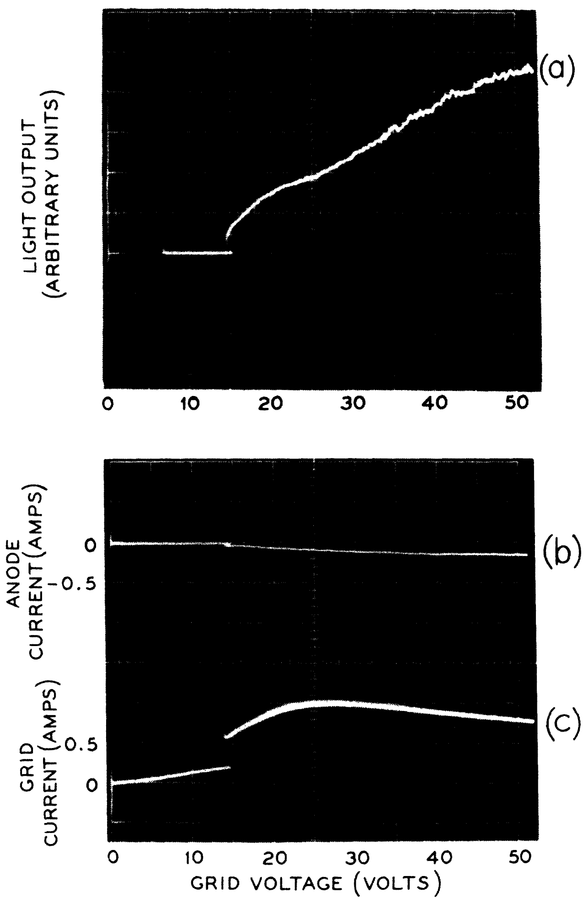

FIG. 2. Laser oscillation of 2.06-μ line of xenon observed in the electron tube: (a) the light intensity output; (b) the anode or ion current; (c) the grid current. All the oscilloscope traces are plotted versus electron energy or grid voltage.

plotted versus the electron energy or the grid voltage. We see a jump in both the grid and anode currents. The oscillation is not observed before the current jump which, as described earlier, occurs at the onset of the desired potential distribution.

Figures 3(a), (b), and (c) show measurements of single-path gain (upper traces) of the 1.1526-μ line of neon at the pressures of 0.2, 0.4, and 2 Torr, respectively. The lower traces in Fig. 3 are the corresponding grid currents.

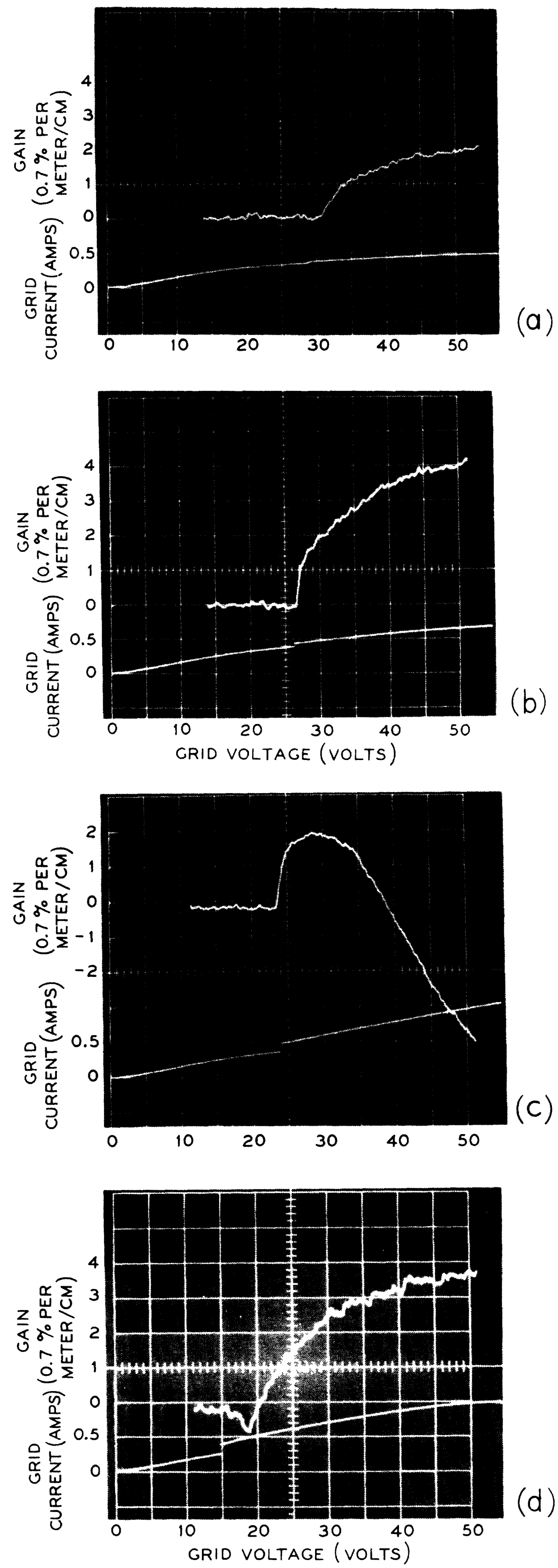

FIG. 3. The single-path gain of the 1.152-μ line of neon measured in the electron tube. (a) Neon−0.2 Torr; (b) neon−0.4 Torr; (c) neon−2 Torr; (d) neon−0.5 Torr and xenon 0.04 Torr. The upper traces show the gain per meter and the lower traces indicate the grid current.

The gain is linearly proportional to pressure up to 0.4 Torr. At high pressure and high grid voltage, we observe sharp obsorption instead of gain. The phenomenon is interesting for possible applications to light modulation or switching. The light output can easily be modulated by the grid voltage which controls the flow of the primary current.

Figure 3(d) shows similar gain measurements for neon at 0.5 Torr mixed with xenon at 0.04 Torr. In this case we observe an absorption peak near 19 V, which may be identified as population of the lower laser state ($2p_4$) by direct electron impact. The gain then builds up slowly as the grid voltage increases further. This agrees with the theoretical consideration[6] that the lower state is not connected to the ground state optically and should exhibit a resonance type of cross section, whereas the opposite is true for the upper state which should have a cross section increasing with the electron energy beyond the potential of excitation.

Based upon the above measurements, we have calculated[7] a cross section of excitation of 0.43 $\times 10^{-18}$ cm^2 for the neon $2s_2$ state at an electronic energy of 30 V. The smallness[8] of the cross section does justify the small gain measured previously in the pure neon discharge lasers.[9] The calculated cross section increases linearly from the potential of excitation up to about 30 V and then increases slowly beyond. It is 0.63 $\times 10^{-18}$ and 0.71×10^{-18} cm^2, respectively at 40 and 50 volts.

As pointed out earlier, the density distribution of the primary electrons is computed from the measured grid current using a diffusion equation including losses due to inelastic collisions. To substantiate our calculation, we have used this electron-density distribution to calculate the ion current from the known cross section of ionization.[10] The calculation agrees with the measured ion current within 10% for all the combinations of the grid voltage and pressure used in the experiments. The details of the calculation will be published elsewhere by one of the writers. We should also point out that the experiments were performed by pulsing the grid voltage at a rate of 200 cps and with a pulse width of 1 msec. The single-path gain was measured using a locking amplifier synchronized with the grid pulses. The time constant of integration is 2 sec. The grid voltage was varied very slowly during the experiment.

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[4]We have also calculated the lifetime of the primary electrons in the grid-anode space, which is not larger than twice the transit time of the electrons in vacuum. The energy lost in elastic collision is negligible.

[5]For example, we neglect the population of the lower laser state. This may be justified from the following argument: The lower state is not optically connected to the ground state and should have a small cross section by electron impact, and its population should be further reduced because of its short lifetime.

[6]H. S. W. Massey and E. H. S. Burhop, Electronic and Ionic Impact Phenomena (Clarendon Press, Oxford, 1952).

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[8]H. Maier-Leibnitz has given the cross sections of inelastic collision for neon up to the electron energy of 24 volts. To resolve his results unto cross sections of different excited states is difficult. However, from the theoretical calculation (based on j-l coupling), the cross section of 2s states should be three times that of $2s_2$. In this sense, our result is smaller than that given by Maier-Leibnitz (see, for example, reference 6), and also has a different energy dependence.

[9]C. K. N. Patel, J. Appl. Phys. 33, 3194 (1962).

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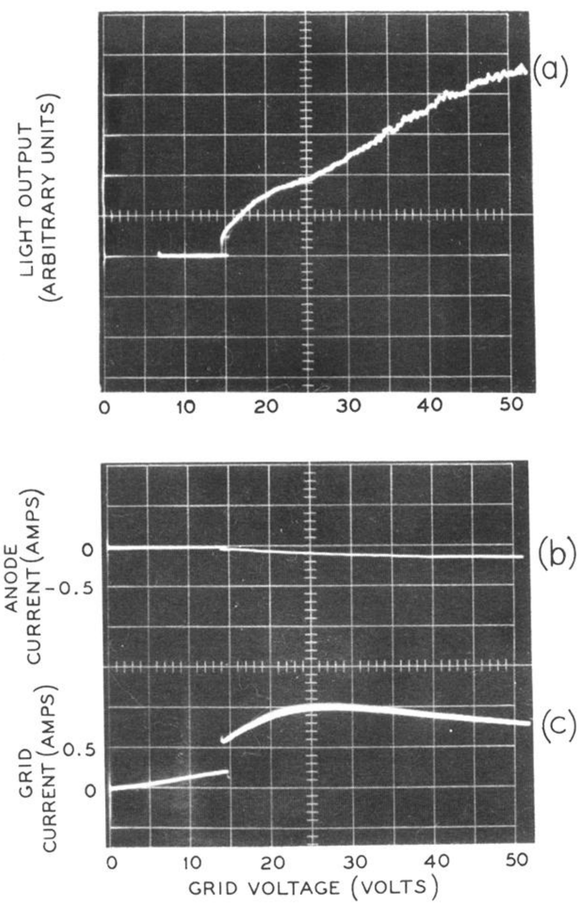

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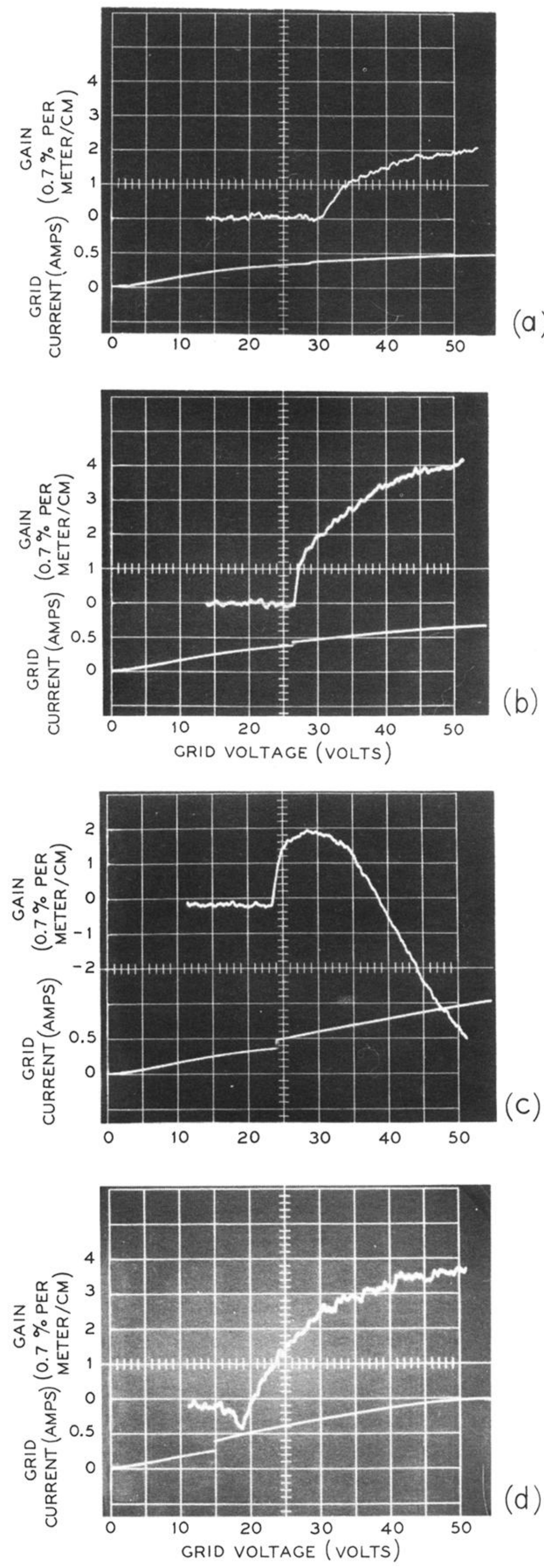

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