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Extremely Low Threshold Current Strained InGaAs/AlGaAs Lasers by Molecular Beam Epitaxy

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Using solid source Molecular Beam Epitaxy we have grown strained layer InGaAs/AlGaAs graded index, separate confinement heterostructure lasers operating at 1.01μm. For broad area, uncoated, Fabry-Perot devices, with cavity lengths in excess of 3000μm, the threshold current density is 56A/cm^2, a value which we believe to be the lowest ever reported for laser diodes in any materials system. The internal quantum efficiency for these lasers is 88%, while the materials losses are 1.8cm^{-1}.

Approved
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The extended wavelength capability ($0.9 \leq \lambda \leq 1.1\mu m$) afforded by strained layer InGaAs/AlGaAs laser diodes has recently stimulated much interest, due to the device possibilities for 980nm Er^{3+}-doped fibre pump lasers and for frequency doubling applications into the blue/green region of the visible spectrum[1]. The removal of the heavy hole/light hole degeneracy due to the strained nature of the active region in these devices also promises reduced Auger recombination rates and lower threshold current densities than for unstrained GaAs/AlGaAs material[2], although to date this promise has not been fulfilled in the case of material grown by Molecular Beam Epitaxy (MBE).

In this paper we report the growth, by solid source MBE , of strained InGaAs/AlGaAs graded index, separate confinement heterostructure lasers operating at 1.01μm, having threshold current densities of $56 A/cm^2$ for uncoated, broad area devices with cavity lengths in excess of 3000μm. We believe this result to be the lowest threshold current density reported for strained InGaAs/AlGaAs laser diodes, superseding the value of $114 A/cm^2$ reported previously for material grown by MBE[3] and the value of $65 A/cm^2$ reported previously for material grown by Metalorganic Vapour Phase Epitaxy (MOVPE)[4]. Clearly, the MBE strained InGaAs/AlGaAs materials technology has now overtaken the state of the art AlGaAs/GaAs material, which has a reported minimum threshold current density of $78 A/cm^2$ for broad area, Fabry-Perot cavity devices[5].

The MBE growth of the laser material was performed in a Vacuum Generators V80H machine. A schematic diagram of the laser design is given in figure 1. During growth of the 0.5μm n^+-GaAs buffer layer (i) the substrate temperature was ramped from 600°C to 700°C. The 0.12μm

n^+-$Al_xGa_{1-x}As$ graded region (ii), graded from x=0.33 to x=0.7, and the 1.8μm $Al_{0.7}Ga_{0.3}As$ cladding layer (iii) were grown at a constant temperature of 700°C. The graded index region (iv) was again grown at a constant temperature of 700°C. On initiating growth of the GaAs core region (v), the substrate temperature was ramped rapidly to 565°C, at which temperature the InGaAs quantum well was grown. No interruption of the MBE growth was used for this low threshold device. Laser growths in which an interruption was inserted showed higher threshold current densities and higher lasing energies, in agreement with the observations of Choi and Wang on MOVPE grown material[4]. This low threshold current density is also achieved in the absence of any graded composition, strain relief InGaAs buffer layer, or of any AlAs/GaAs superlattice smoothing layers prior to growth of the InGaAs quantum well active layer. The GaAs following the active quantum well was grown as the temperature was ramped from 565°C to 700°C. The graded index region (vi), the $Al_{0.7}Ga_{0.3}As$ cladding layer (vii) and the graded region (viii) were grown at 700°C. During growth of the GaAs cap, (ix), the substrate temperature was ramped to 500°C, at which point the p-type doping level was increased to the level of $5x10^{19}cm^{-3}$. All temperatures quoted above were measured using an infrared pyrometer.

Broad area devices of width 260μm were fabricated by standard photolithographic processing and wet chemical etching with H_2SO_4: H_2O_2: H_2O to separate adjacent lasers on a bar by removal of the intervening p^+-GaAs cap. Ti-Pt-Au metallisation was used as the top surface, p-type contact and Au-Ge-Ni, alloyed at 415°C for 15 seconds in a rapid thermal annealer, was used as the back surface, n-type contact. Initial pulsed testing at low power levels was done without any device heat sinking. For testing CW, devices were soldered p-side down onto gold plated BeCu heat sinks.

Light output measurements as a function of injected current were performed using a calibrated InGaAs detector. The output wavelength was approximately 1.01µm. In figure 2 we show the threshold current density as a function of cavity length for the broad area devices. The threshold current density decreases with increasing cavity length due to the diminishing contribution of the mirror losses relative to the distributed materials losses. For device lengths in excess of 3000µm the threshold current density saturates at the value of 56A/cm^2. We attribute this extremely low value of the threshold current density to three factors, (i) the high quality of the MBE grown material, (ii) the large optical confinement produced by the high aluminium content cladding regions and (iii) the facilitation of population inversion in the active region due to the strain induced symmetrisation of conduction and valence band densities of states[6]. The high quality of the MBE grown material results from optimising separately the substrate temperatures for both the AlGaAs cladding and the InGaAs quantum well active layer. In the growth of GaAs/AlGaAs lasers, Tsang[7] has shown the necessity of eliminating mid-gap, non-radiative recombination centres in the AlGaAs cladding by growing at temperatures around 700°C, while Eng and co-workers[3] had produced the lowest threshold MBE InGaAs laser material by growth in a temperature regime where In desorption is significant. This last requirement makes the wavelength control of devices difficult, since the InGaAs well composition and thickness will be a strong function of the substrate temperature.

To determine the internal quantum efficiency, η_i, and the materials losses, α_i, we plot the reciprocal of the differential external quantum efficiency, η_d, against the cavity length in figure 3. The differential external quantum efficiency reaches a value of 83% for a cavity length of 400μm, decreasing to 62% at a cavity length of 3000μm. The internal quantum efficiency inferred from the zero length intercept of figure 3 is 88%, while the materials losses inferred from the gradient have the extremely low value of 1.8cm^{-1}. In figure 4 we show CW light output power per facet as a function of injected current, and the current voltage characteristic, for a device of length 1000μm. A power output of 0.5W per facet is achieved at an injected current of approximately 1.64 Amps. The maximum power output is limited by the current drive capabilities of our laser test facilities. The series resistance of this device is high, $\approx 0.5\Omega$, due to the large width of the intrinsic region. These devices also act as good Stark effect waveguide modulators at the wavelength corresponding to the laser output. Results of modulator experiments will be published subsequently.

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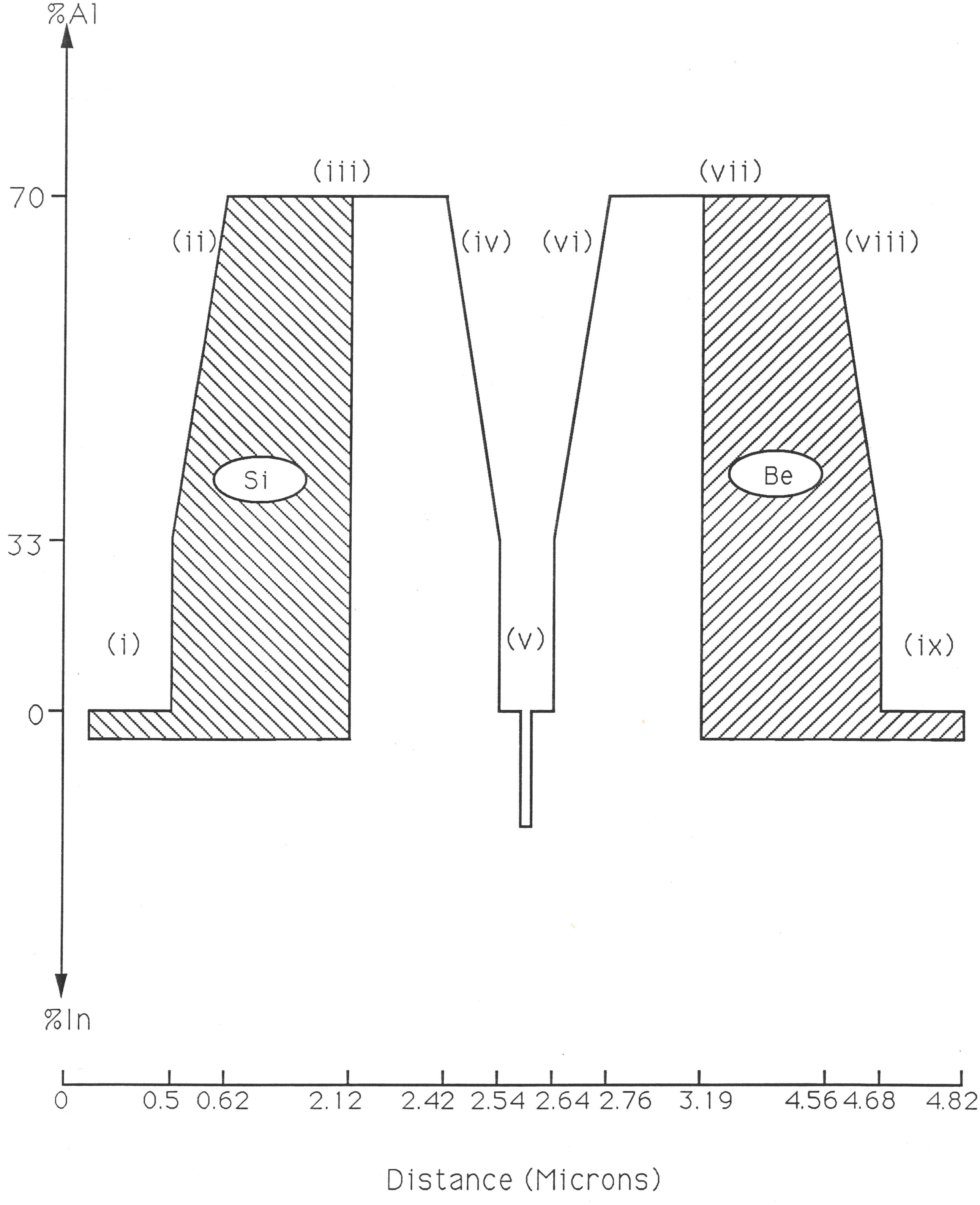
Figure Captions

Figure 1. Schematic diagram of the graded index separate confinement heterostructure laser.

Figure 2. Threshold current density, J_{th}, as a function of cavity length for the uncoated, broad area, Fabry-Perot cavity devices.

Figure 3. Reciprocal differential external quantum efficiency, η_D, as a function of cavity length for as cleaved devices.

Figure 4. Continuous Wave light output as a function of drive current, and the current voltage characteristic for a device of length 1000µm.


%Al
70
33
0
%In
(i)
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(iii)
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(vi)
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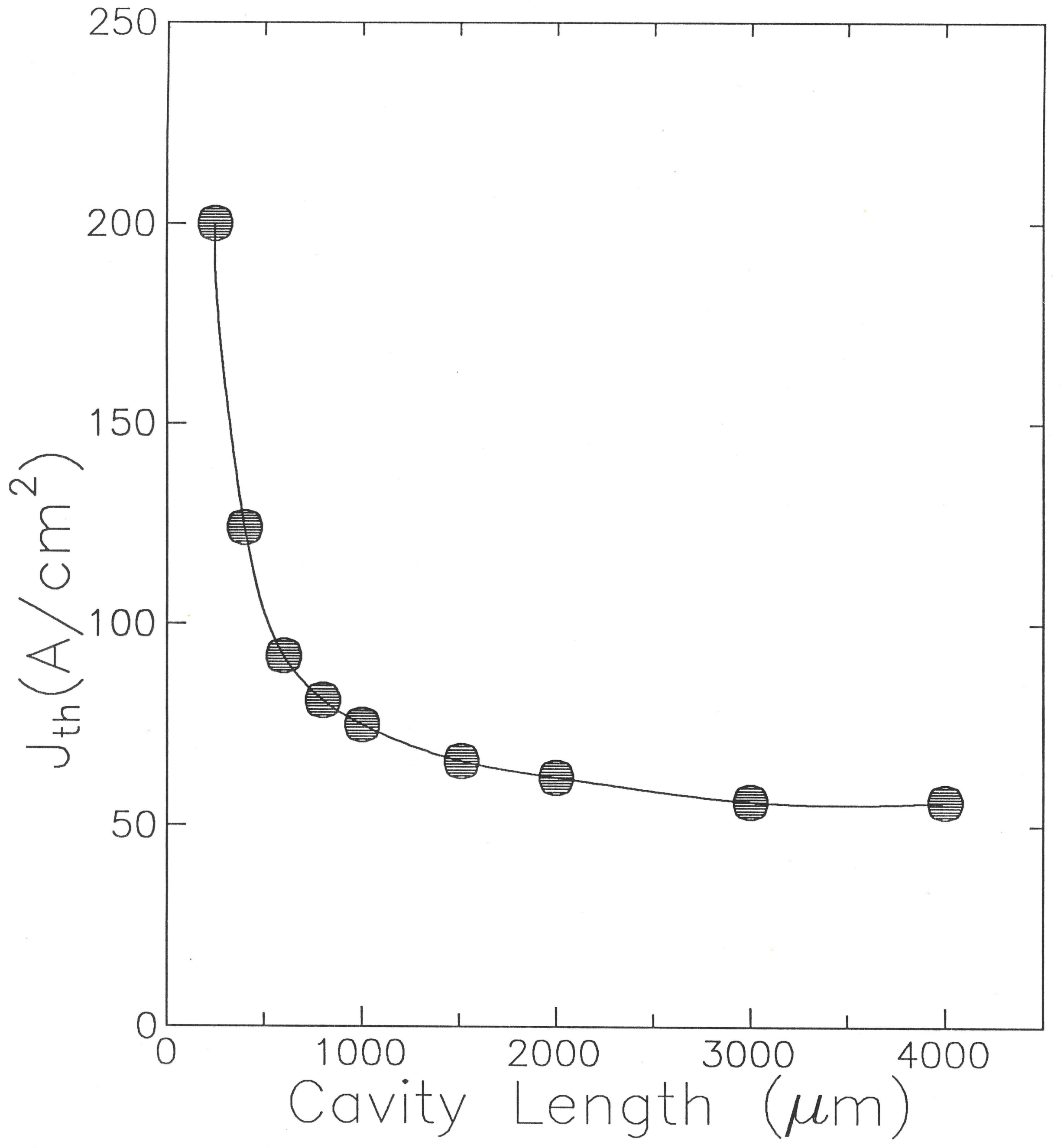
(viii)
(ix)
Si
Be
0
0.5
0.62
2.12
2.42
2.54
2.64
2.76
3.19
4.56
4.68
4.82
Distance (Microns)



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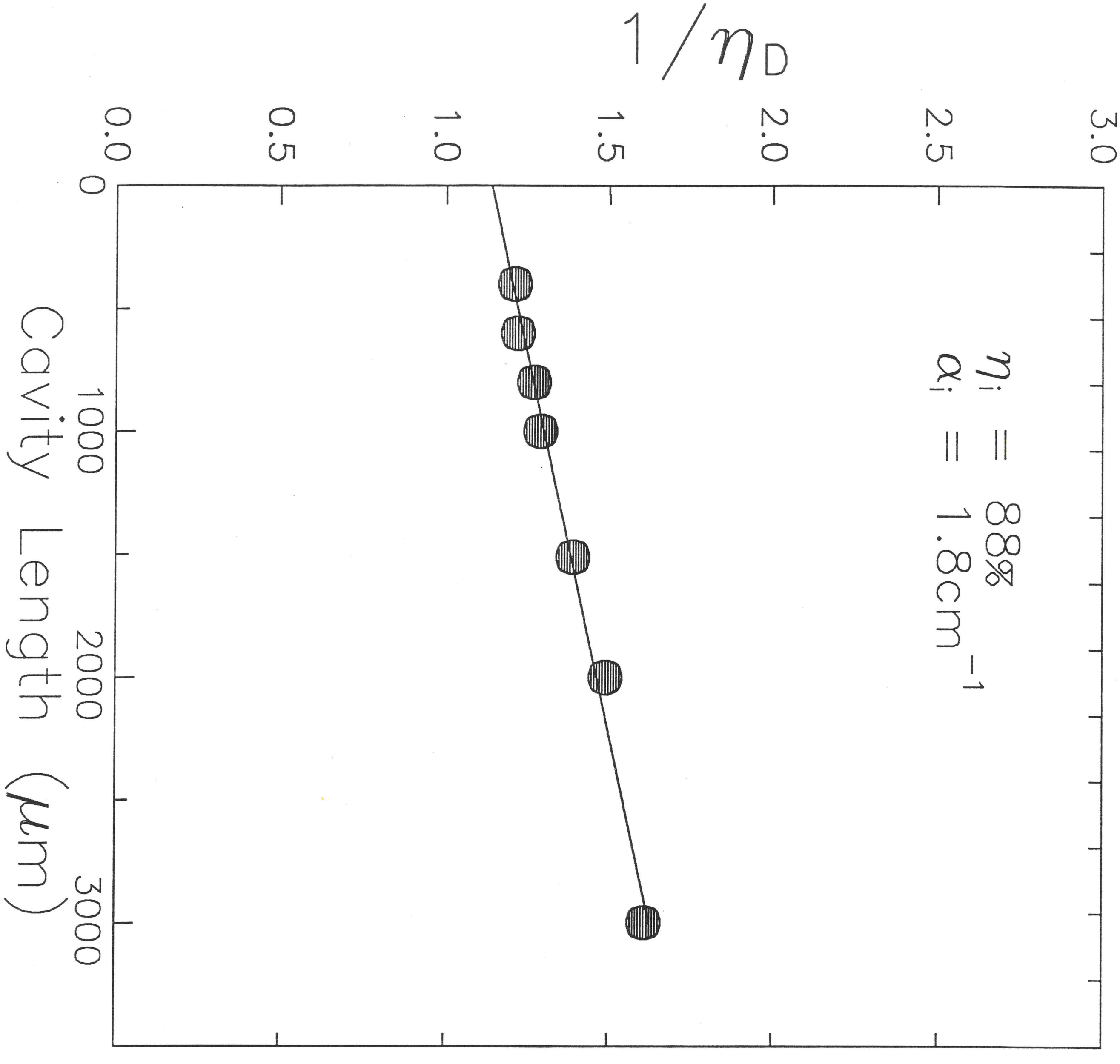
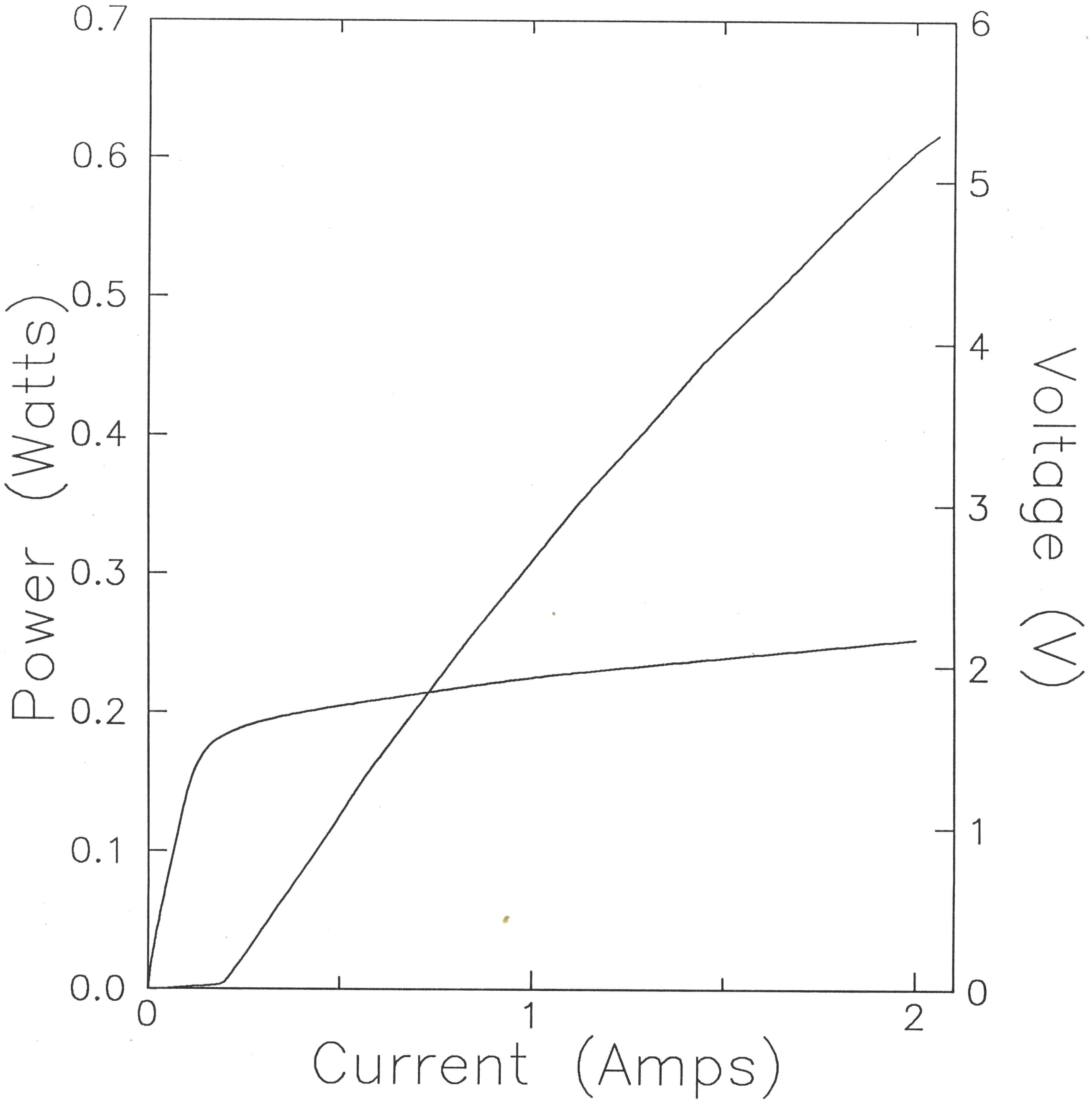
200
150
100
50
0
$J_{th}(A/cm^2)$
0
1000
2000
3000
4000
Cavity Length (μm)



1/η_D
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
1000
2000
3000
Cavity Length (μm)
η_i = 88%
α_i = 1.8cm^{-1}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0.2
0.3
0.4
0.5
0.6
0.7
Voltage (V)
0
1
2
3
4
5
6
Current (Amps)
0
1
2